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Climate Change on the Urban Scale – Effects and Counter-Measures in Central Europe

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1. Introduction

According to the Intergovernmental Panel on Climate Change (IPCC, 2007), global climate change, which will lead to a temperature increase of the lower atmosphere, can be traced to an increased concentration of carbon dioxide (CO₂) and other infrared-active gases. Urban agglomerations are particularly affected because, in contrast to the surrounding rural areas, they are characterised by a high population density, a considerable extent of tightly sealed and rough surfaces and air pollution.

Of the consequences projected for central Europe, among which are changes in the precipitation patterns and the weather regime, this article focuses exclusively on the thermal and air-hygienic effects. These impacts pose a high risk for the inhabitants of every city, not only those of cities prone to flooding. Therefore, select measures are described that can counter the excess heating and the increase in temperature-dependent air pollution at the local level. The countermeasures presented in this chapter refer mainly to adaptation measures, although there exists a smooth transition between adaptation and mitigation.

2. Urban excess heating

Compared with non-built-up space outside conurbations, cities have higher air and surface temperatures, which occur particularly during local (autochthonous) meteorological conditions characterised by low winds and limited cloud cover. Among other factors (Table 1), high daytime radiation, a negative radiation balance (Q^*) in the evening and at night as well as a limited atmospheric exchange guarantee the development of a positive horizontal temperature difference between urban (t_u) and rural, non-built-up surroundings (t_r ; $\Delta T_{u-r} > 0$ K). This phenomenon is called the urban heat island (UHI).

Influencing factor (IF)	Sign of correlation coefficient between UHI and IF
Cloud cover	–
Wind speed	–
Anthropogenic heat emission	+
Bowen ratio, β^1	+
Population	+
Sky view factor, SVF ²	–
Ratio building height/street width (H/W)	+
Surface sealing	+
Green- and water-surface area/total area	–
Latitude	+

¹ $\beta = Q_H/Q_E$; (Q_H/Q_E = turbulent sensible/latent heat flux density)

² SVF: degree to which the sky is obscured by the surroundings at a given location

Table 1. A selection of meteorological and structural factors influencing the UHI (source: Kuttler, 2009)

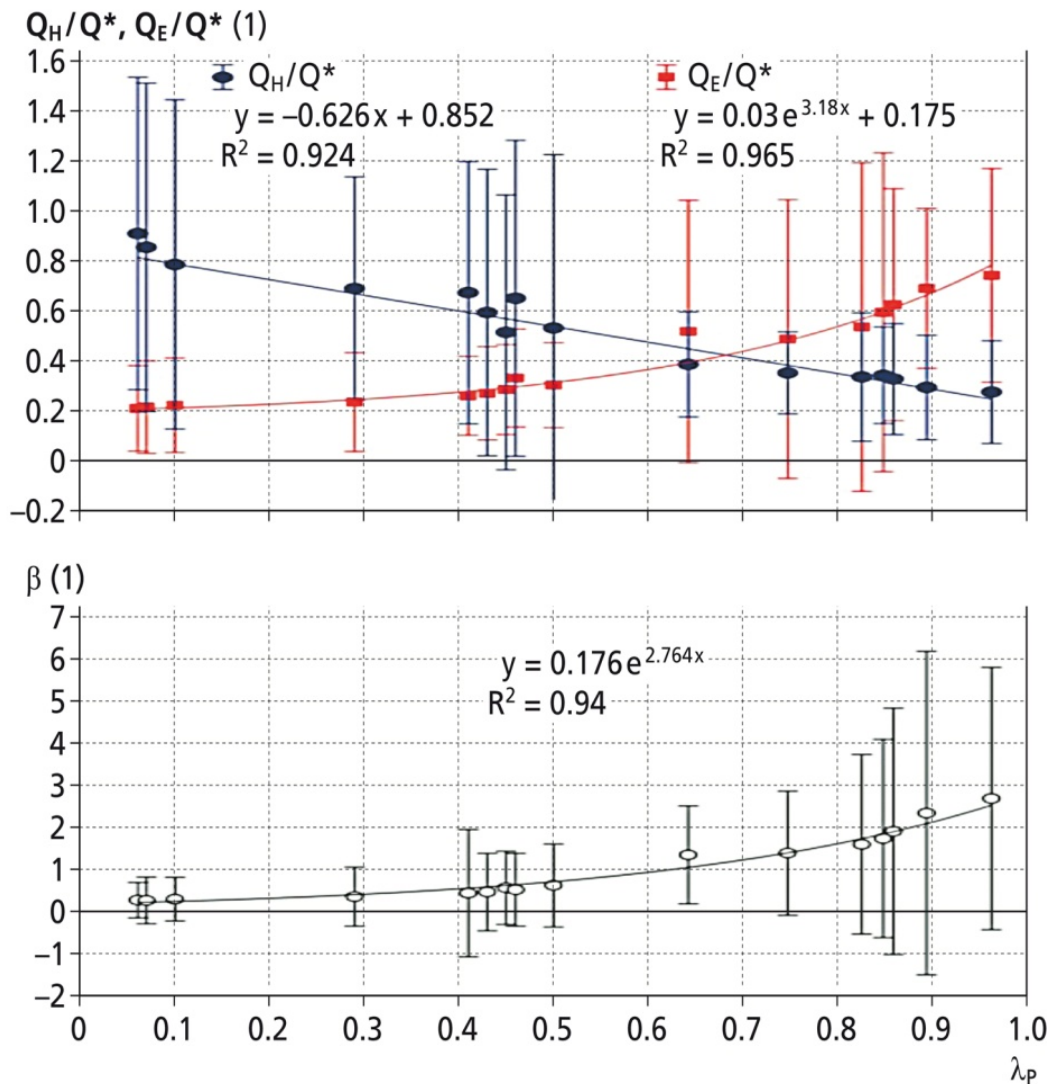
UHI can be categorised according to the types of vertical structures in an urban area as follows:

- below ground (subterranean UHI),
- on the surface (surface UHI),
- in the urban canopy layer (UCL UHI) and
- in the urban boundary layer (UBL UHI).

Subterranean and surface UHIs are predominantly caused by radiation and most frequently found in combination with sealed surfaces. The UCL and the UBL UHIs are caused by the heating of the air and are consequently much less congruent with sealed areas. Furthermore, the three-dimensional structure of the UCL and the UBL UHIs allows the wind to change their shape.

2.1. Factors influencing urban excess heating

In addition to the long-wave radiation fluxes ($L\uparrow$, $L\downarrow$), the dominance of either sensible or latent heat fluxes (Q_H , Q_E) is important to the heating of a city atmosphere. The Bowen ratio ($\beta = Q_H/Q_E$; Table 1) determines the respective proportion of Q_H and Q_E in specific cases. The surface type, i.e., whether an artificially sealed or a natural evaporation surface, is the decisive factor for the energy partitioning (Fig. 1). For example, if the plan area density (λ_P) is low, the major part of the energy resulting from the radiation balance (Q^*) in bright and sunny weather is transferred via the latent heat flux (Q_E) to the UBL without heating the layer significantly (Fig. 1 a). In such a case ($\lambda_P = 0.1$), the Bowen ratio reaches $\beta < 0.25$. However, where the surface is completely sealed ($\lambda_P = 1.0$), the sensible heat flux (Q_H) dominates (here, approximately 80 % of Q^*) with a Bowen ratio of $\beta > 2$.



¹⁾ Mean 30 min values and σ_1 , $Q^* > 0 \text{ W/m}^2$; sectors of wind direction and λ_p dependent calculation of urban/suburban data; 8/ 2010 – 4/ 2011; soil heat flux (Q_s) omitted

Figure 1. Ratios of Q_E/Q^* and Q_H/Q^* (a) and Bowen ratios β (b) as a function of plan area density (λ_p) in Oberhausen, Germany (213,000 inhabitants; source: Goldbach & Kuttler, 2012)¹⁾

Therefore, weather conditions and the degree of sealing substantially influence the UHI intensity, which displays temporal and spatial dependencies.

As shown in Fig. 2, the air-temperature differences between a completely sealed urban location (t_u) and an undeveloped location in the rural environment (t_r) display typical diurnal and annual cycles in the UCL. Hence, the following conclusions can be made for central European metropolises:

- UHI_{max} usually occurs in the evening or night and usually lasts until the early morning.
- During the day, no or little UHI effect develops.
- The dependency of the UHI on the weather is mirrored in the cellular distribution of air temperatures. However, in cloudy, rainy and windy (allochthonous) weather, the overheating is substantially reduced (October to February).

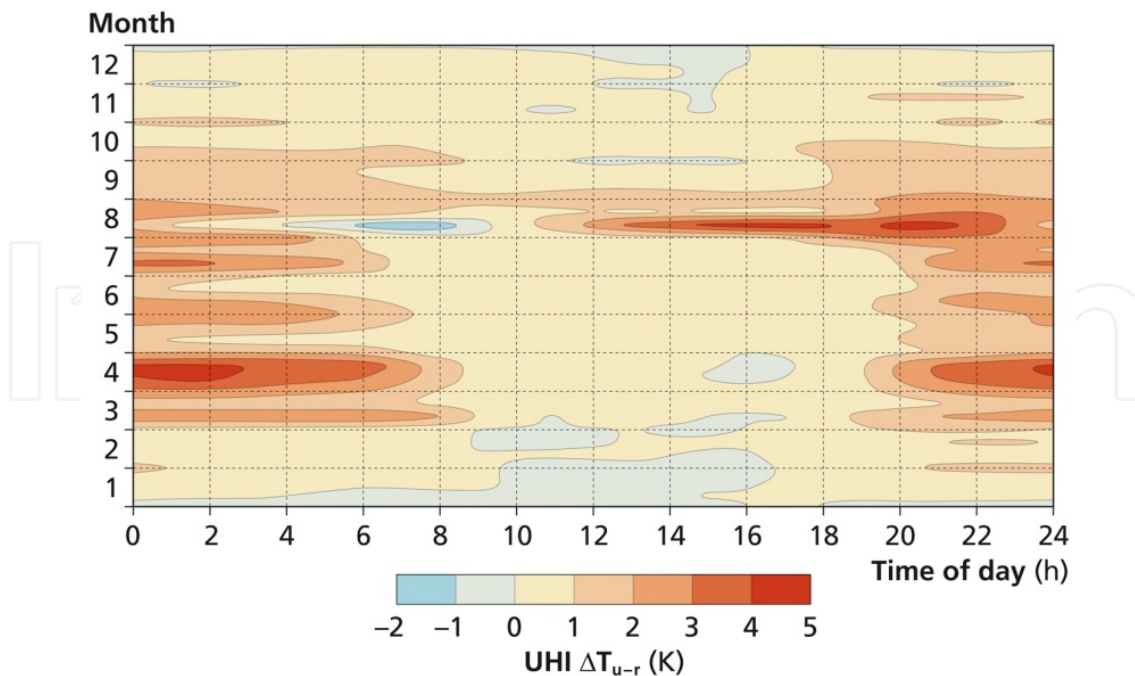
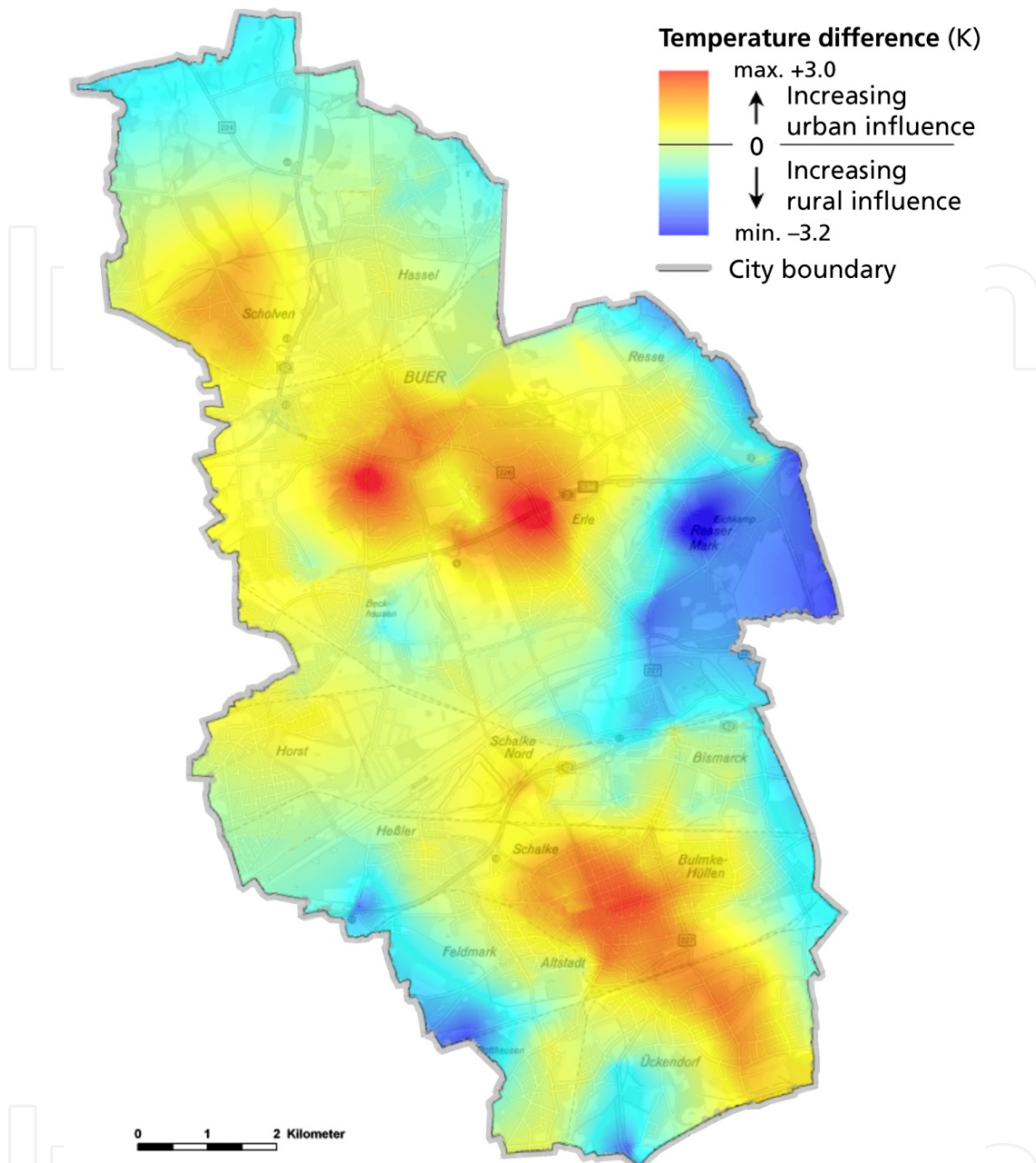


Figure 2. Hourly mean values of the UCL UHI (ΔT_{u-r}) in Bochum, Germany (375,000 inhabitants; 10/2006 – 10/2007)

Compared with the surrounding countryside, a spatially homogeneous overheating within the city limits seldom occurs and can display a highly heterogeneous pattern as a function of plan area density (λ_P). The expression “heat archipelago of a city” is a suitable term for the phenomenon (Hupfer & Kuttler, 2006). The example shown in Fig. 3 clearly emphasises the higher air temperatures of overheated, tightly sealed inner-city and industrial areas (red) compared with natural areas (blue) such as forests and undeveloped open countryside with lower air temperatures.

As a result, the most significant horizontal differences are found between the densely built-up areas of the city ($\lambda_P = 0.9$) and the unsealed and open countryside ($\lambda_P = 0.14$) with the above-mentioned peaks in the nocturnal hours (Fig. 4). The differences are far less significant between the inner city and the suburbs ($\lambda_P = 0.39$) because the degree of surface sealing in the two areas is more similar than in the first case. The thermal behaviour of an intra-urban park (1.2 ha) is particularly interesting. The park’s air is cooler than that of the city. However, the temperature does not reach the low value of the countryside. The comparably higher air temperatures detected in the park are caused by the warmer atmosphere of the surrounding sealed areas, preventing the green area’s air temperature from decreasing further (Kiese, 1995). In the end, the value of overheating in the park is approximately half the value measured in the densely built-up inner city.

To calculate the intensity of a UHI for urban agglomerations with an easily ascertainable parameter, the number of inhabitants is frequently used as a substitute value. In contrast to other size-related specifications, this value is usually easily obtainable. As the results of an exemplary evaluation for German cities demonstrate (Fig. 5), the urban excess heating can be positively correlated with the population figures.



¹⁾ "Calm and clear weather conditions" according to Düttemeyer, 2000, resp. Polster, 1969

Figure 3. UHI in the urban canopy layer during a night with clear and calm weather¹⁾ in Gelsenkirchen, Germany (298,000 inhabitants; 4/2011)

However, only 44 % of the values are represented through the exponential fit, i.e., the statistical connection is not very tight, because numerous other factors can exert an influence on the UHI in addition to the population figures. These other factors include, e.g., anthropogenic heat (Böhm, 1998; Quah & Roth, 2012), the traffic density, the city size, the allocation and mixture of sealed and unsealed surfaces, the proportion and distribution of green spaces, the vegetation (leaf-area index (LAI); leaf-area density (LAD)), the building materials, the building volumes, the proportion of high-rise buildings and topographical features.

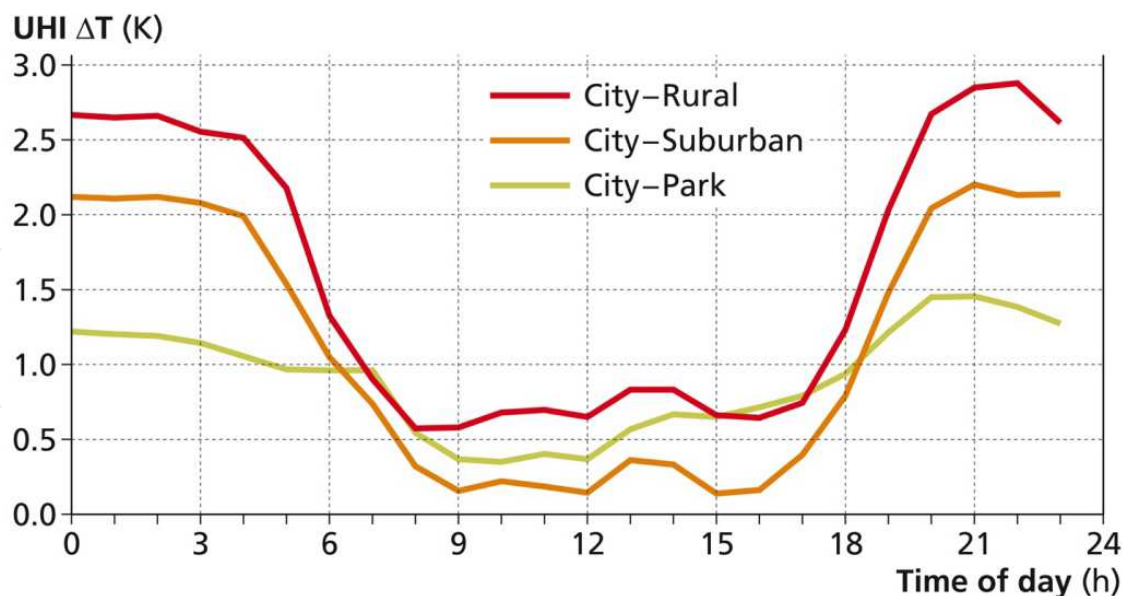


Figure 4. Hourly mean values of excess heating between the city and an urban park, the city and a suburban site and the city and a rural site in Oberhausen, Germany, for 76 calm and clear days (08/2010 – 07/2011)

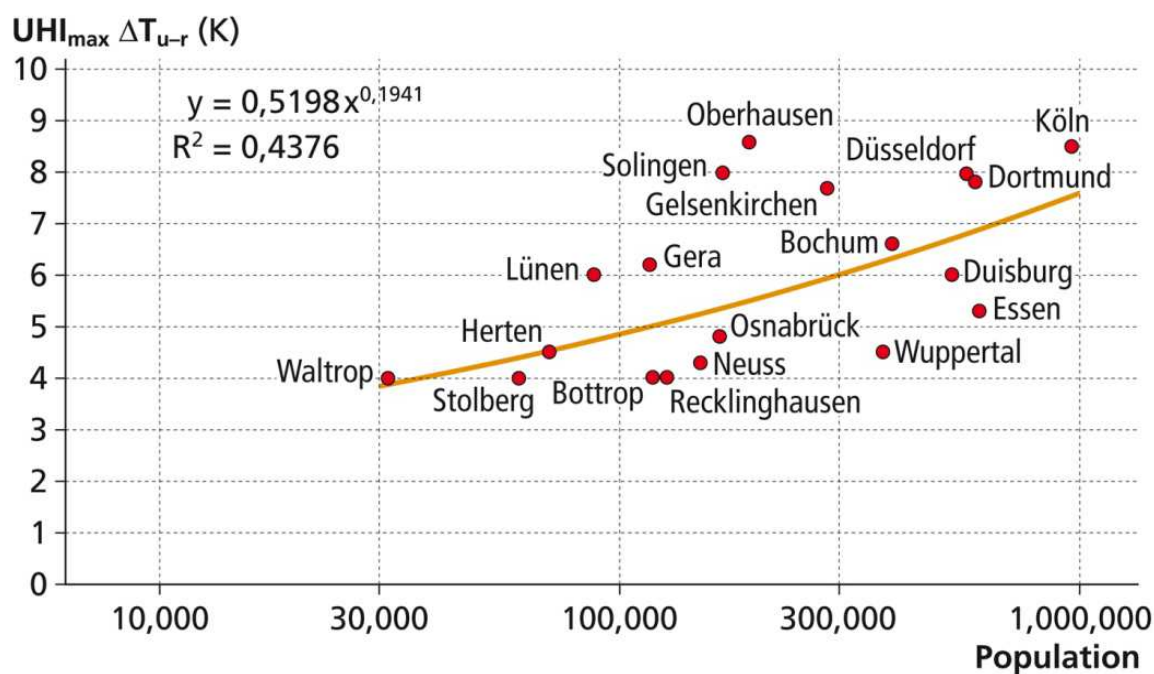
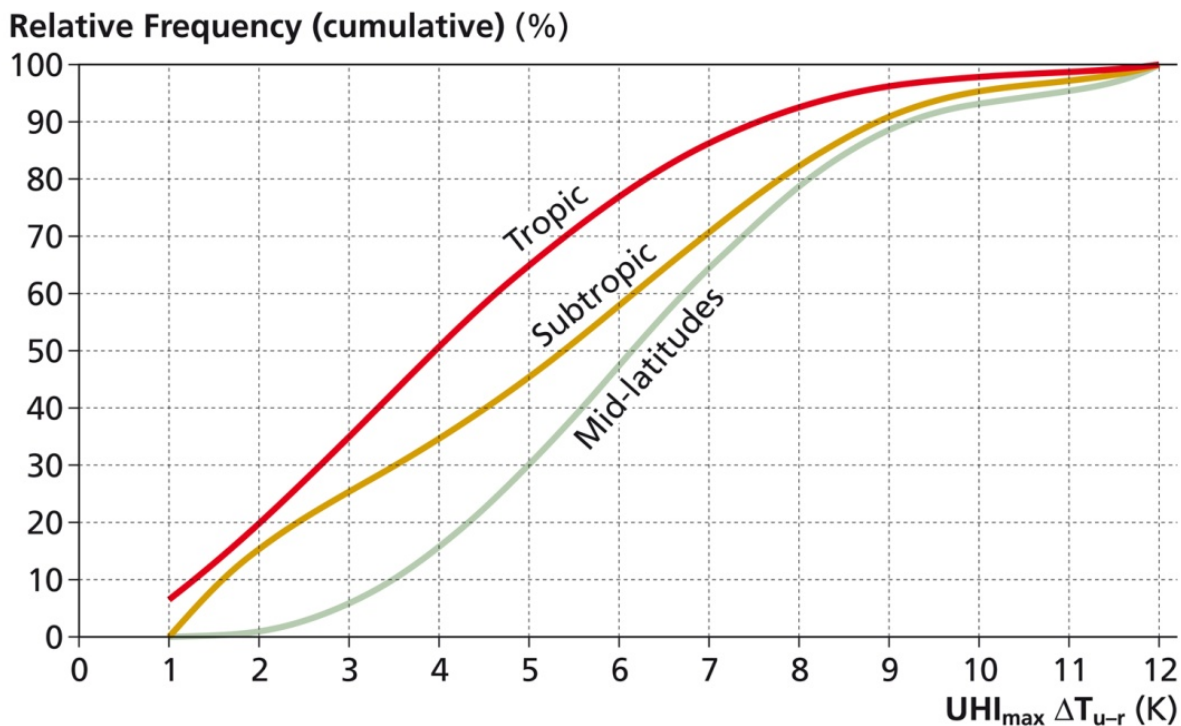


Figure 5. Maximal UHI intensity ($\Delta T_{(u-r) \max}$) in the urban canopy layer as a function of population for selected German cities (data basis: stationary and mobile measurements; source: Kuttler, 2010a)

Generally, the intensity of a UHI is dominated by local and regional influences. However, large-scale influences can be identified, albeit in severely weakened form. If selected UHI intensities are assigned to three clusters (e.g., tropics, subtropics, mid-latitudes) according to the cluster's latitudes (Fig. 6), positive correlations can be observed. For instance, for the tropical cluster, a mean value of 4 K can be calculated for UHI_{\max} , whereas 5 K can be calculated for the subtropical cluster and 6 K for the mid-latitudes (50 % quantile each; for

more information regarding the basis for the cluster calculations, see Wienert & Kuttler, 2005, Fig. 6). This correlation, which was first assumed by Kratzer (1956) but never statistically proven, appears to be mainly caused by anthropogenic heat and the radiation balance (input and output parameters according to Terjung & Louie, 1972).



¹⁾ Basis for the cluster calculations: city population, height above sea level, topographic features (coast, plain, valley), climate classification according to Terjung & Louie, 1972

Figure 6. Cumulative frequency distribution of UHI_{max} in the urban canopy layer for different climate zones (i.e., tropics, subtropics, mid-latitudes; source: Wienert & Kuttler, 2005)¹⁾

2.2. Urban excess heating and its effect on humans

Those city districts that develop heat islands under current climatic conditions can be expected to increase thermal stress for their inhabitants due to the projected increase in frequency, intensity and duration of heat spells under global climate change. This increased thermal stress will occur unless timely measures are taken in urban and environmental planning to counter these developments.

The comparison of climatic event days, meaning values of a meteorological variable fall below or exceed thresholds within one day, helps to quantify the degree to which the thermal climate will change. Thus, a *summer day* is defined by a maximum air temperature of $\geq 25^\circ\text{C}$.

For instance, if the mean value of the daily maxima of air temperature in Essen, Germany, is 21.9°C (Fig. 7) under the current climatic conditions in the summer months June, July and August, an average number of 26 summer days can be calculated. If, according to the IPCC

(2007), the mean values of the daily maxima of air temperature in Essen rise by 2.3 K until the year 2100, 18 additional summer days will occur, amounting to a total of 44 summer days. Under the current conditions, on 6 days the air temperature maxima reach values of $\geq 30^\circ\text{C}$ (*hot day*). Under climate change, this number will double to 12 days.

These numbers demonstrate that for estimating the consequences of thermal climatic change, observing the change of the annual mean temperature alone is insufficient. In the respective distribution statistics, the significant change will be in the quantity of peak values.

A distinction between humid (allochthonous) and dry (autochthonous) heat is required when analysing specific periods of high air temperatures or heat spells in central Europe. From the perspective of human biometeorology, humid heat creates a higher thermal stress for the human body than dry heat due to increasingly difficult transpiration. Humid heat is frequently caused by the advection of humid and warm air, for instance, air originating from the Mediterranean, whereas dry heat is developed locally by a combination of strong solar radiation and stagnating air masses under the influence of high pressure.

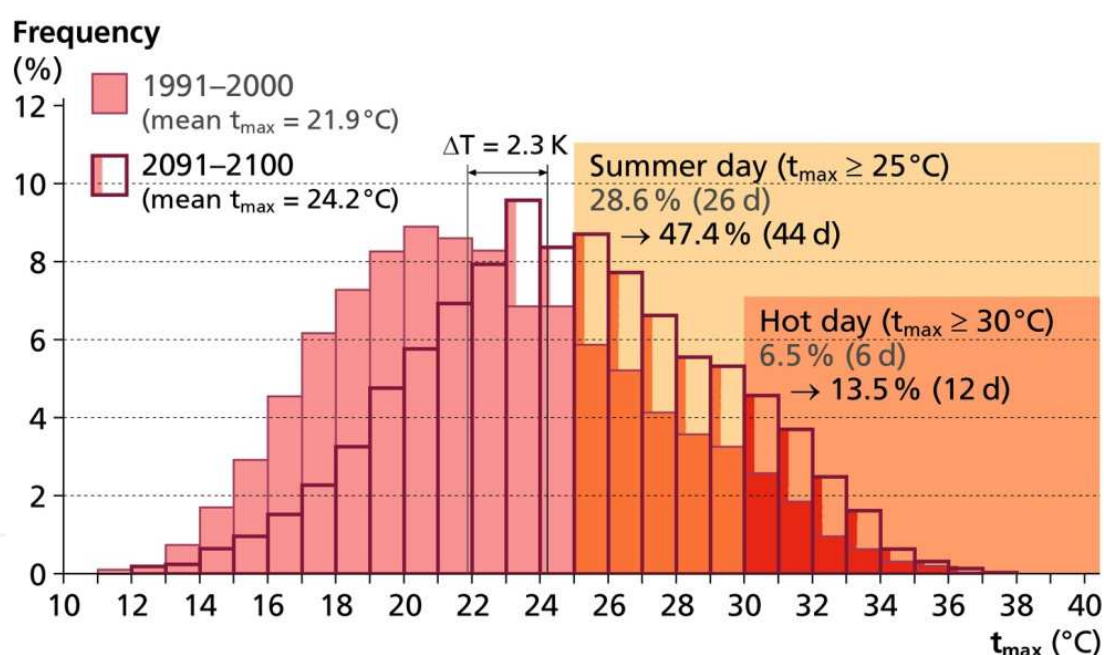
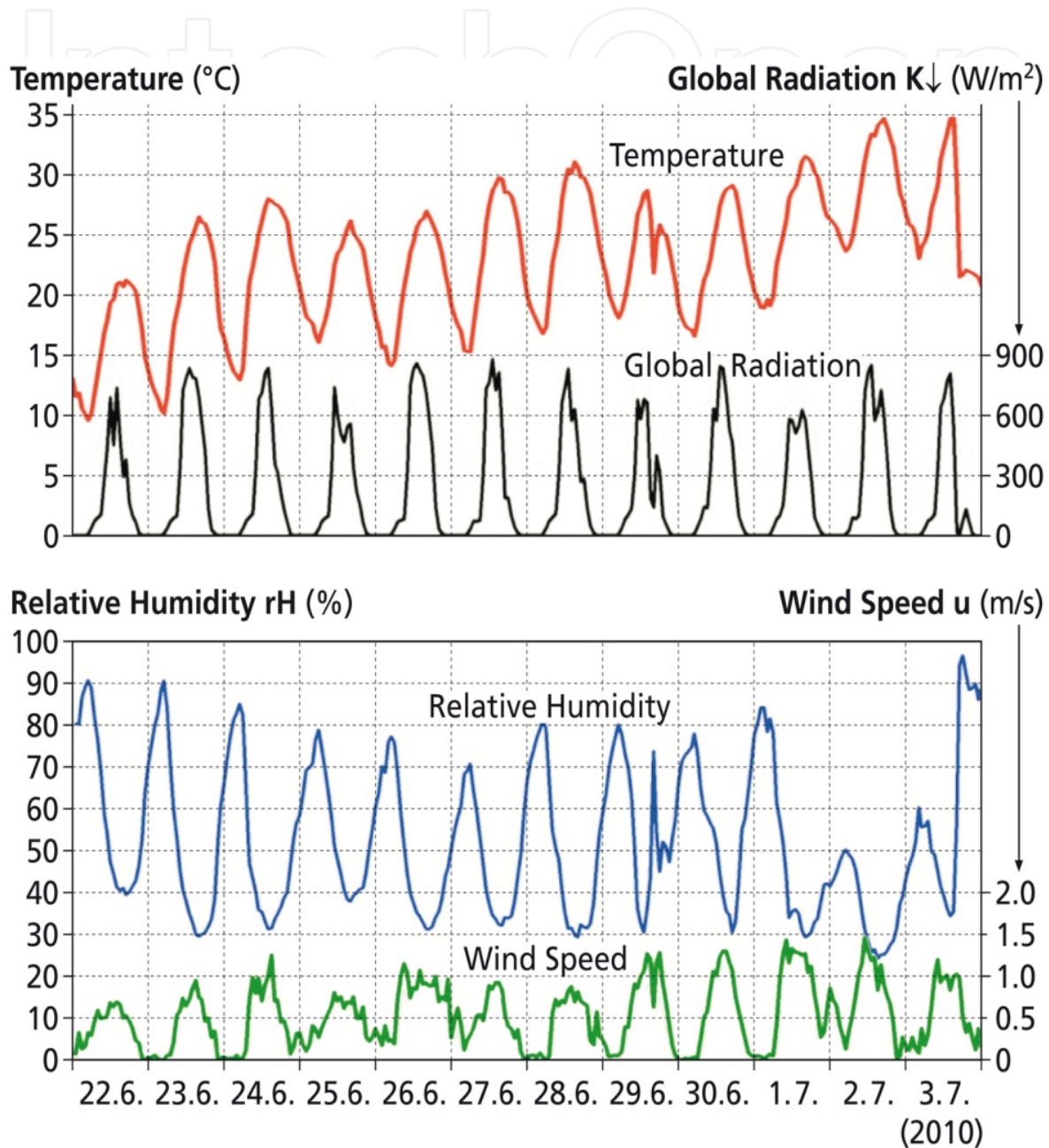


Figure 7. The distribution frequency of the daily maxima of air temperature in summer months (JJA) in Essen, Germany, in the past (1991 – 2000) and future climate (2091 – 2100) (source: Modell WETTREG/ECHAM5; IPCC-SRES-scenario: A1B, modified; here according to Kuttler, 2011a)

Repeated and distinct diurnal cycles of global radiation, wind speed, relative humidity and air temperature suggest an autochthonous heat episode (Fig. 8). The development of the air temperature from day to day displays an increase, even with relatively similar maxima of daily global radiation flux density. At the beginning, a maximum of 22°C (22.06.2010) and a minimum of 10°C in the night were observed. These values increased to 34°C and 22°C , respectively, at the end of the heat spell (04.07.2010). This increase is caused by the heat storage effect of the buildings. The thermal stress is not only caused by the high

temperatures during the day but also by the daily reduction of the nocturnal cooling effect, which can have a detrimental effect on the recreational function of the sleep of the population (Höppe, 1984).



¹⁾ Data of the University of Duisburg-Essen climate station, Campus Essen, 22.06.2010 – 04.07.2010; (source: P. Wagner, pers. comm.)

Figure 8. Hourly mean values of selected meteorological elements (t , K_{\downarrow} , rH , u) during a fair-weather episode in Essen, Germany¹⁾

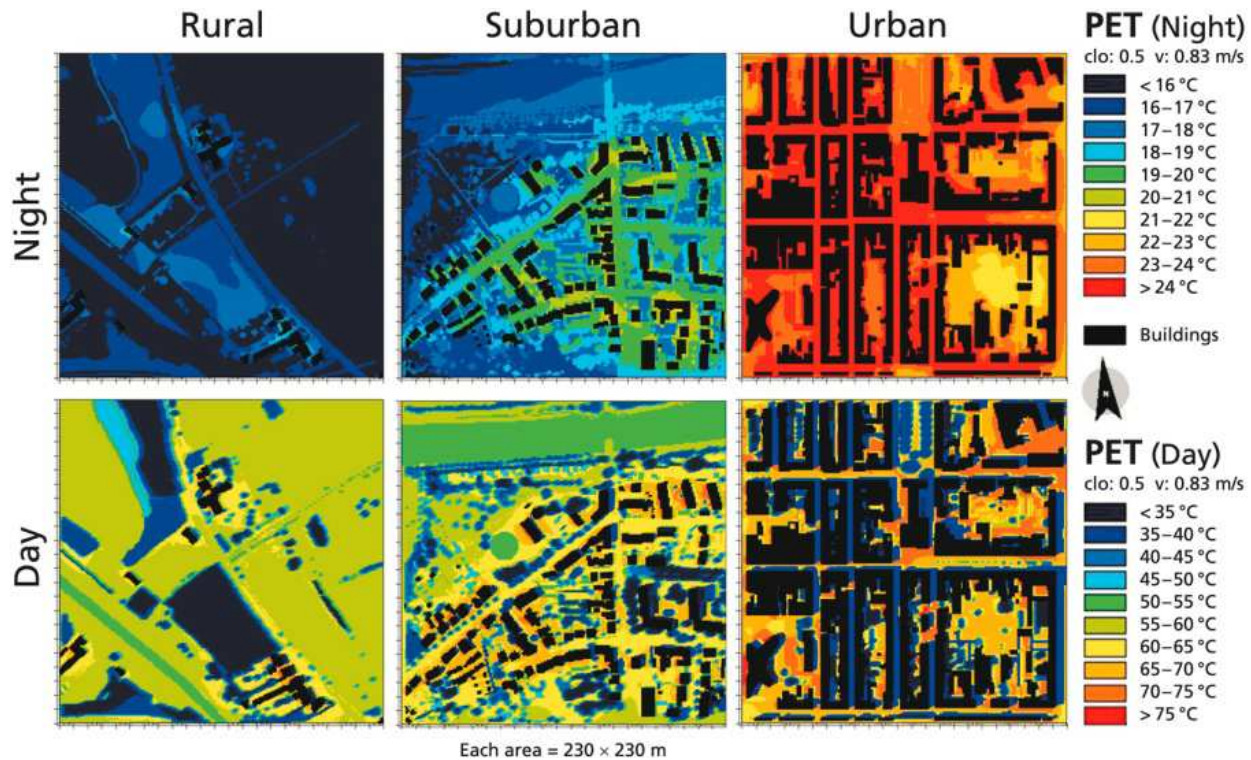
Thermal stress, to which the population is exposed for considerable periods of time, can result in increased rates of morbidity and mortality, as the increase of mortality rates in central Europe during the two heat waves in August 2003 demonstrated (Jendritzky, 2007; Souch & Grimmond, 2004). To enable an objective classification of the thermal stress perceived by humans, human-biometeorology employs several thermal indices which include the physically measurable data of meteorological elements, such as air temperature, humidity, radiation temperature and wind speed as well as human physiological factors, such as physical activity, or clothing type.

Of the available thermal indices (Mayer, 2006), the physiologically equivalent temperature (PET), which is calculated based on the above-mentioned values, is chosen as a point of reference (for details, see Verein Deutscher Ingenieure, Association of German Engineers (VDI, 2008)). By the way all indices, including the PET values, are mainly governed by the radiation temperatures of the enclosing wall surfaces to which a person is exposed. The PET range is categorised into different classes according to the thermal perception and the physiological stage of stress of individuals and is given in °C (Table 2).

PET	Thermal perception	Stage of stress
< 4°C	Very cold	Extreme cold stress
4-8°C	Cold	Great cold stress
8-13°C	Cool	Moderate cold stress
13-18°C	Slightly cool	Slight cold stress
18-23°C	Comfortable	No thermal stress
23-29°C	Slightly warm	Slight heat stress
29-35°C	Warm	Moderate heat stress
35-41°C	Hot	Great heat stress
> 41°C	Very hot	Extreme heat stress

Table 2. The Physiologically Equivalent Temperature (PET), its thermal perception by and stage of stress for humans (source: Matzarakis & Mayer, 1996)

Fig. 9 shows examples of the varying thermal stress of an individual (PET) according to land use during a day of clear and calm summer weather for a rural, a suburban and an urban location, comparing day and night.



¹⁾ clo: heat transfer resistance of the clothing, v: wind velocity

Figure 9. ENVI-met simulation results: the PET current state for three plan areas (rural, suburban and urban), with a comparison of day and night conditions in Oberhausen (source: Müller, pers. comm.)¹⁾

The model simulation was executed with the model ENVI-met (Bruse & Fleer, 1998) and generally mirrors the lesser thermal stress in the open countryside in comparison with the two urban plan areas, although „extreme heat stress“ also occurs in unshaded rural locations. However, the PET value is significantly higher in the city, particularly where no shade of buildings or trees reduces the radiation temperature. How significantly solitary canopy trees influence the PET values can be seen in the lower right image of Fig. 9. Approximately in the middle of the image, an east-west road displays a strong but localised reduction of the thermal stress due to solitary trees in its eastern section.

In sum, depending on the general weather conditions, cities are more or less overheated in contrast to the surrounding countryside. Therefore, even under the current climate conditions, urban agglomerations can be regarded as harbingers of the thermal aspects of global climate change. As noted, thermal stress in summer is caused by the UHI and has detrimental effects on the population.

3. Urban air quality

In the central European agglomerations, ozone (O₃), nitrogen dioxide (NO₂) and particulate matter (PM₁₀) are air pollutants of present and future significance that in higher concentrations have harmful effects on humans (e.g., Bell et al., 2010; Ebi & McGregor, 2009; Revich & Shaposhnikov, 2010). Nitrogen dioxide is created as a secondary pollutant through

the oxidation of primary emitted NO. Additionally NO₂ is emitted in large quantities as primary air pollutant (Kourtidis et al., 2002). However, changes in the atmospheric concentration of NO₂ do not depend significantly on temperature. Therefore, the temperature increase caused by global climate change should have little impact on the increase of this air pollutant. For this reason, the behaviour of NO₂ concentrations will be disregarded in the following observations. Only the temperature dependency of the urban air constituents ozone and particulate matter will be analysed.

3.1. Ozone

Because high temperatures and intense solar radiation are important preconditions for the formation of the secondary trace substance ozone, ozone concentrations are expected to increase in the future due to the increasing number of heat waves (Kuttler & Straßburger, 1999; Lin et al., 2001). Fig. 10 shows an example of the temperature-dependent formation of ozone. The calculated regression curve allocates an air temperature of 20.5 °C to an ozone concentration of 50 µg/m³. Thus, a doubling to 100 µg/m³ is probable at 28.1 °C, and a tripling of the initial value can be seen at 32.5 °C. One reason for this exponential increase is that the precursor gas peroxyacetyl nitrate (PAN), which contributes to ozone formation, decomposes increasingly fast at rising air temperatures (> 25 °C), thereby releasing nitrogen dioxide, which is the basis for ozone formation in the troposphere.

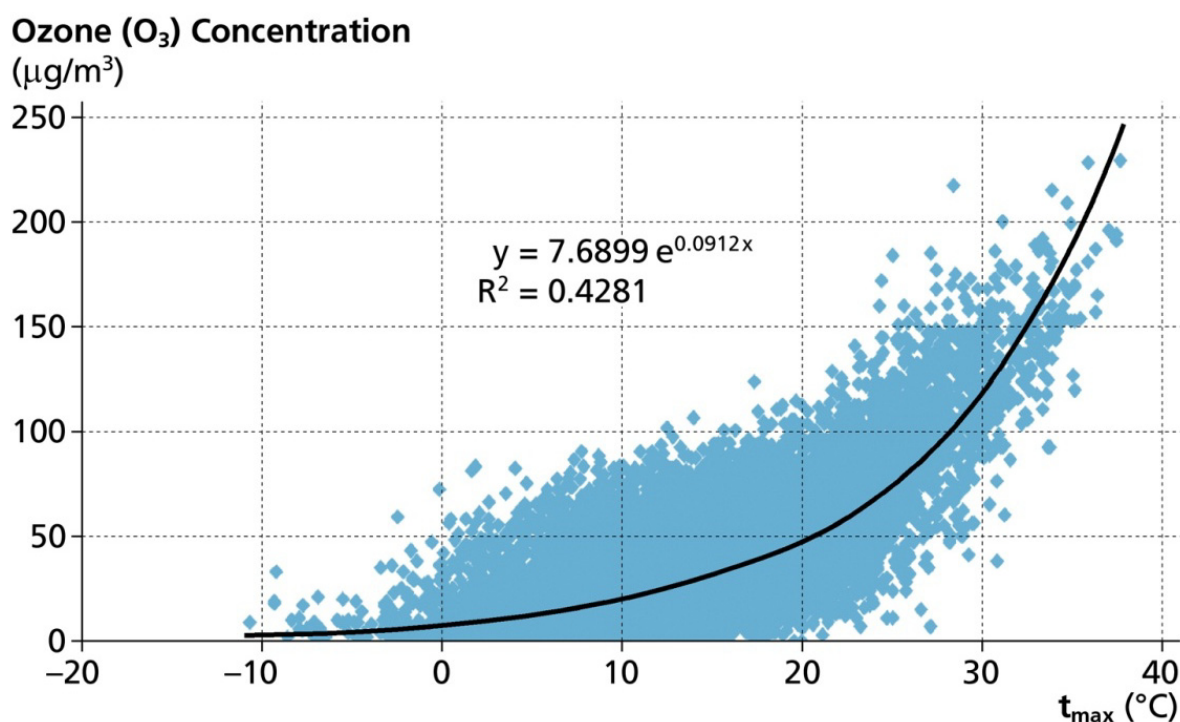


Figure 10. The correlation of the daily maximum ozone concentration and the air temperature at an industrial site in the Ruhr Area (Duisburg-Walsum, 1984 – 2007; source: Melkonyan, 2011)

The volatile organic compounds (VOC) are another group of ozone precursor substances. They can be categorised in two groups: anthropogenic VOCs (AVOCs; for instance, benzene,

toluene and xylene) and biogenic VOCs (BVOCs; for instance, isoprene, α -pinene and limonene (Sharkey et al., 2008)). The latter VOCs are emitted by deciduous and coniferous trees and shrubs when temperatures are high. The plant physiology is not sufficiently understood, however, thermally triggered stress reactions of the vegetation have been discussed (Kesselmeier & Staudt, 1999; Sharkey et al., 2008). Even though BVOCs are expected in the urban atmosphere only at low concentrations due to the usually low vegetation density, the emission rates are highly temperature-dependent. Therefore, even in urban areas, summer weather with strong solar radiation will lead to additional ozone formation by biogenic trace substances. This increase occurs particularly if vegetation is dominantly composed of plants that emit BVOCs on a large scale, the so-called high-emitters (Benjamin & Winer, 1998). For this reason, at certain urban locations, BVOC concentrations (e.g., isoprene) can be produced (Fig. 11) that are several times higher than the AVOC concentrations (e.g., benzene). Additionally, the figure shows the high dependency of isoprene concentrations on the air temperature in contrast to benzene.

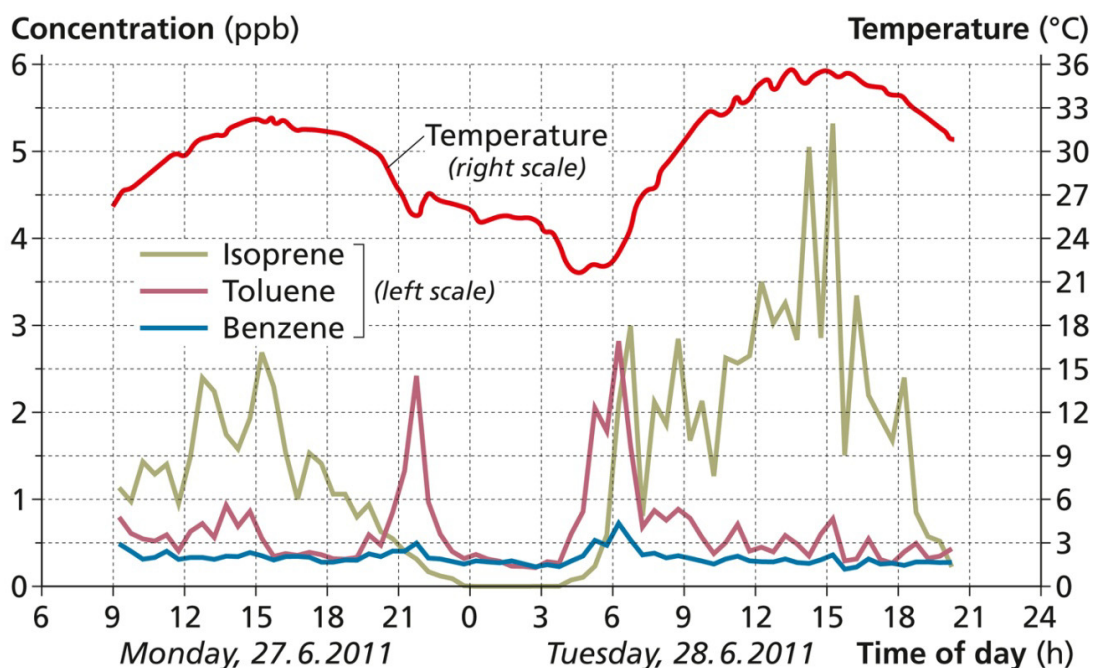
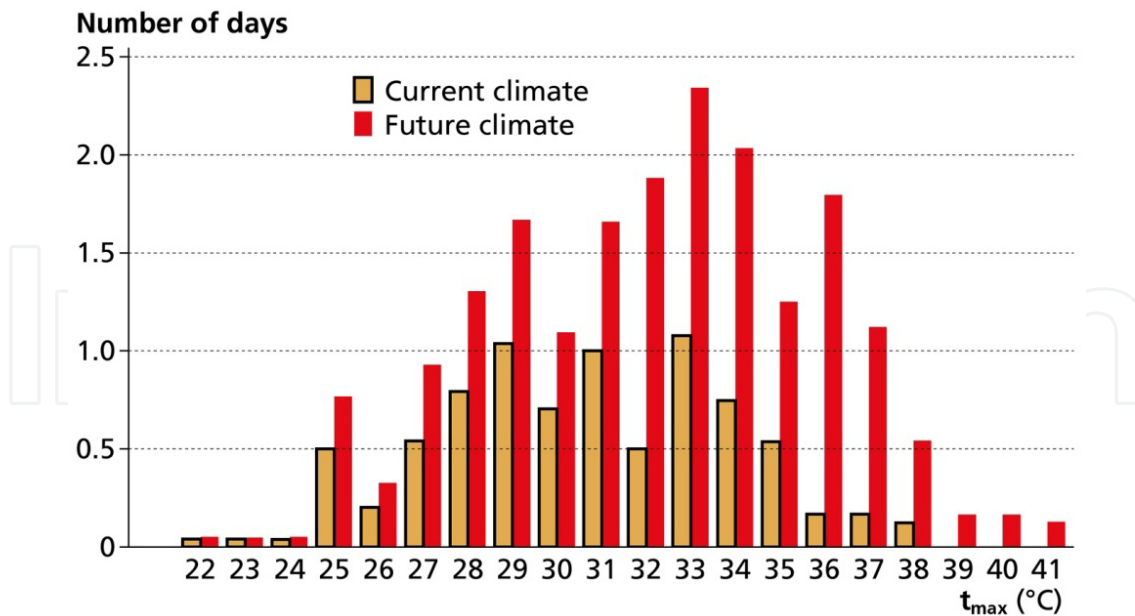


Figure 11. AVOC and BVOC concentrations near a university parking area in Essen, Germany, during hot weather (27.06.2011 – 28.06.2011; source: P. Wagner, pers. comm.)

To avoid increased ozone formation by biogenic VOCs, predominantly those plants should be used as greenery in the city which emit no or only low amounts of these trace substances and belong to the so-called low-emitters.

The number of days on which the ozone level exceeds the acceptable limit for individuals indicates to what degree ozone pollution will change for humans in the future climate. Fig. 12 shows a comparison of the annual number of days with ozone exceedance for the current and future thermal climate at an industrial site in the Ruhr Area, Germany. Accordingly, the mean number of days with ozone exceedance will increase from currently 8 days to 19 days in the future, more than doubling the overall number (Melkonyan, 2011).



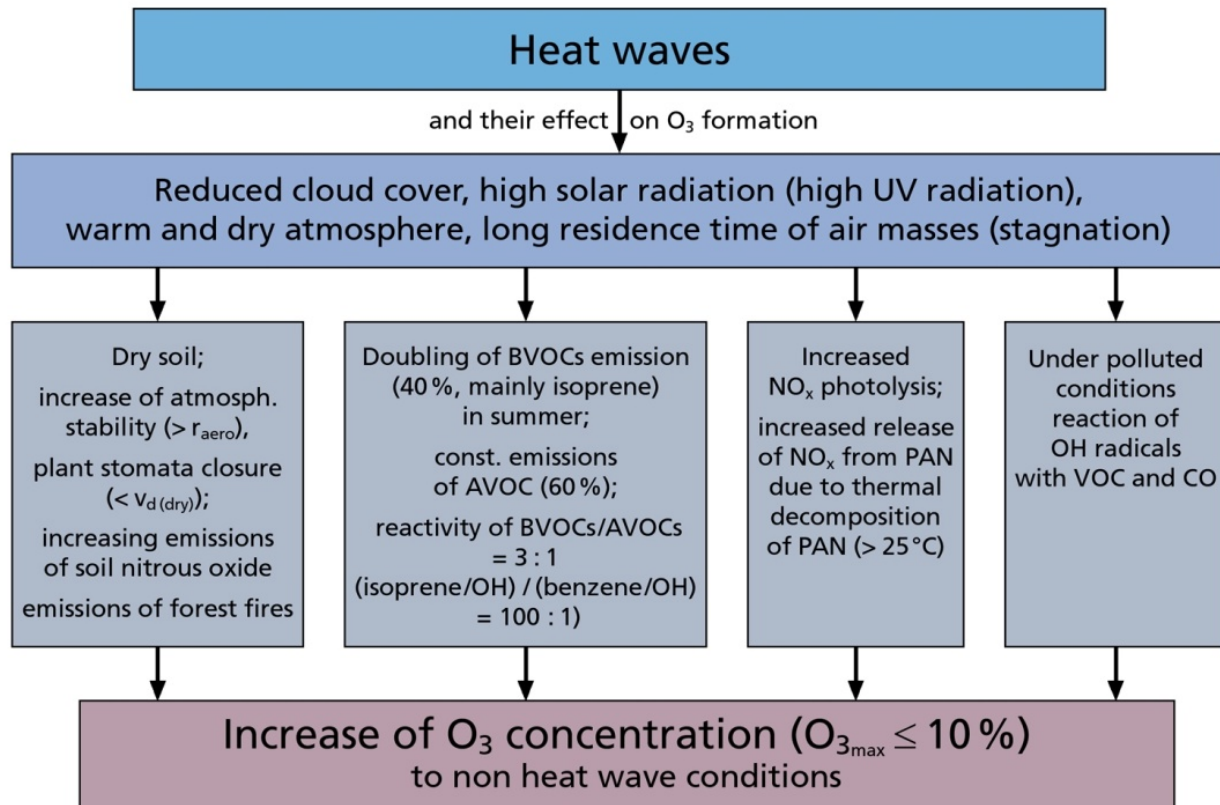
¹⁾ Target value for ozone since January 2010: highest 8-hour mean of one day $\geq 120 \mu\text{g}/\text{m}^3$; 25 days with ozone exceedance allowed per calendar year, averaged over three years

Figure 12. The annual number of days with ozone exceedance¹⁾ for the current (1984 – 2007) and future (2100) thermal climate at an industrial site in the Ruhr Area, Germany (Duisburg-Walsum; source: Melkonyan, 2011)

The increase in ozone concentrations in Germany during calm and clear summer weather with intense solar radiation or during heat waves can be traced to four groups of determinant factors (Fig. 13).

1. Dry soil causes a lower atmospheric deposition velocity (v_d), aerodynamic resistances (r_{aero}) are relatively high and the plant's stomata are prematurely closed. Hence, less ozone reaches the plant's surface or is absorbed by the plant through the stomata.
2. Anthropogenic volatile organic compounds (AVOCs) and biogenic volatile organic compounds (BVOCs) contribute to the overall emission of VOCs in the summer at a ratio of 60:40 with isoprene being a major trace substance of the BVOCs. Although the BVOCs occur at a lower concentration in street canyons than the AVOCs, the reactivity of the BVOCs (e.g., isoprene) – measured in terms of reaction with OH radicals – is increased by a factor of approximately 100 compared with the AVOCs (e.g., benzene). The emission of BVOCs increases exponentially until approximately 40 °C (particularly the isoprene's). However, the emission of AVOCs shows little or no temperature dependency. Thus, ozone formation is expected to increase in city districts with a significant quantity of plants that are high-emitters of BVOCs.
3. Anthropogenic combustion processes lead to the emission of high amounts of NO_x , which results in a higher potential of photolysis in the near-surface air layer and an increased release of the oxygen atoms required for ozone formation. Furthermore, PAN is highly unstable at temperatures exceeding 25 °C, causing the release of ozone precursors.
4. Under polluted conditions in urban areas, the reaction of OH radicals with VOCs and CO leads to ozone formation.

In sum, the projected temperature increase in Germany caused by global climate change is expected to lead to a maximum increase in the ozone concentrations of up to 10 % compared with current peak concentrations.



¹⁾ Benjamin & Winer 1998; Chameides et al., 1988; Dawson et al., 2007; Demuzere & van Lipzig, 2010; Emeis et al., 1997; Forkel & Knoche, 2006; Held et al., 2004; Klemm et al., 2000; Mayer & Schmidt, 1998; Meleux et al., 2007; Meng et al., 1997; Narumi et al., 2009; Pöschl, 2005; Sillmann, 1999; Solberg et al., 2005; Solmon et al., 2004; Straßburger, 2004; Taha, 1996; Wu et al., 2008; Yashuda et al., 2009

Figure 13. Four groups of factors leading to ozone formation during calm and clear summer weather, compiled according to several authors¹⁾

3.2. Particulate matter

Particulate matter is defined as the particle content of the air, which can be categorised into three different modes of size and formation (GDCh, 2010):

- The nucleation mode (ultrafine particles, $\varnothing \leq 100$ nm) with little mass fraction and formation mostly by gaseous precursors, which agglomerate quickly;
- the accumulation mode ($100 \text{ nm} < \varnothing \leq 1,000$ nm); formation mainly through the nucleation mode by adsorption of gases or by coagulation;
- the coarse mode ($\varnothing > 1 \mu\text{m}$); particles originating from deflation and erosion processes or mechanical abrasion and suspension.

The entire class of particles with a particle size of up to $10 \mu\text{m}$ (PM_{10}) is commonly called particulate matter.

Approximately half the particulate matter is directly emitted (primary particles), while the remainder is formed by gas-to-particle conversion (secondary particles). The question whether atmospheric concentration of particulate matter displays a statistical dependency on the air temperature requires a differentiated examination. Neither in the urban nor the rural boundary layer does a significant correlation appear to exist between the overall concentration of PM₁₀ and the air temperature (Melkonyan, 2011).

However, a connection with temperature can be ascertained for certain modes, e.g., for ultrafine and very large particles (for instance, plant pollen).

Among the ultrafine particles, the BVOCs play a special role, being emitted by specific plants in the summer during strong solar radiation. These compounds do not only exert a sustained influence on ozone production, but also affect the aerosol mass. Due to their low vapour pressure, the organic compounds formed during the oxidation of BVOCs adhere to the particles already present in the atmosphere, increasing their overall mass. Several measurements prove (Plass-Dülmer, 2008) that the BVOCs add significantly to the aerosol mass in summer, whereas an influence on the formation of new particles could not be proven (Kiendler-Scharr et al., 2009) or their contribution should at least be viewed as doubtful (Plass-Dülmer, 2008). Under the increasing temperatures of global climate change, this problem is expected to grow. The summer increase of the particle mass likely has an impact on the radiation balance and cloud formation (Pöschl, 2005).

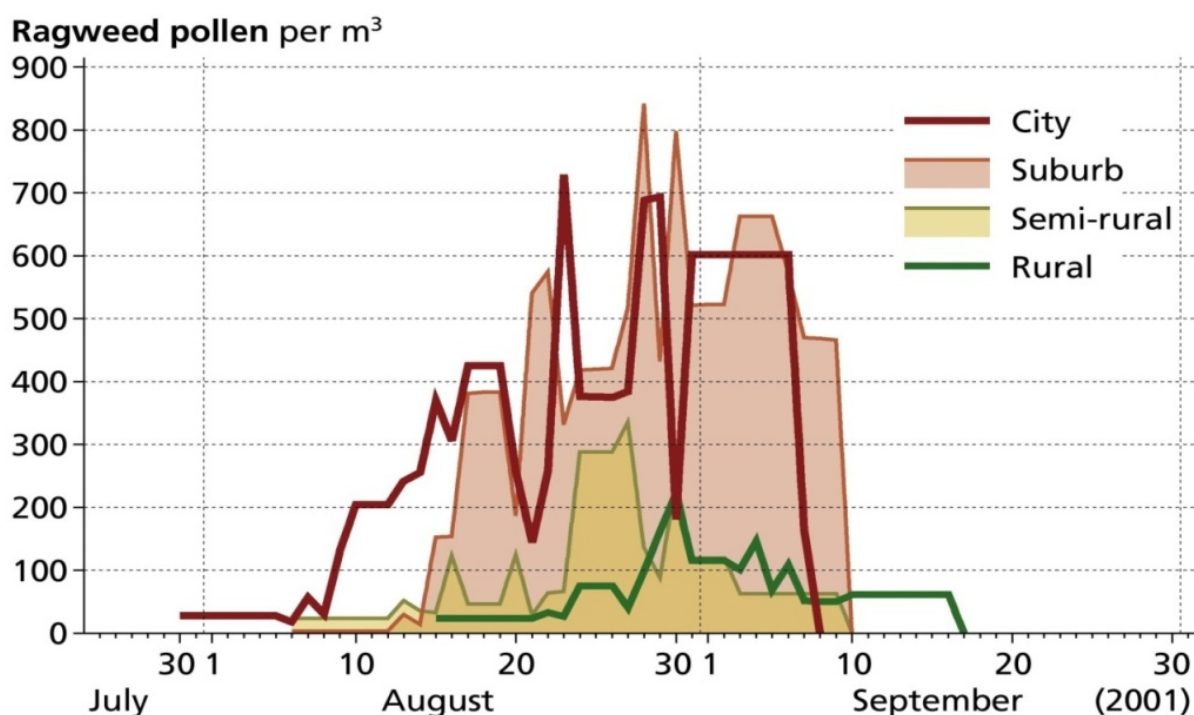


Figure 14. The summer ragweed pollen production for four sites along an urban transect in Maryland, USA, in 2001 (source: Ziska et al., 2003, modified)

In the case of plant pollen ($< 250 \mu\text{m}$), ragweed pollen (*Ambrosia artemisiifolia*) was used to demonstrate (Ziska et al., 2003) that, with higher temperatures and CO₂ concentrations,

pollen dispersal begins significantly earlier in cities than in the surrounding countryside. In addition, a considerably higher pollen count can be measured in cities in comparison with rural areas (Fig. 14). The pollen contains an allergen that is detrimental to human health (Amb a1) and whose production is affected because ragweed is a C₃ plant. Because the growth of C₃ plants is limited by carbon, UHIs and higher concentrations of urban CO₂ boost the production of this allergy-triggering protein. Laboratory research has shown (Ziska & Caulfield, 2000) that pollen production and the number of floral spikes per plant are approximately doubled if atmospheric concentrations of CO₂ increase from 370 ppm (2000) to 600 ppm (2050).

Other types of plant pollen, such as that of the birch, are triggered in their allergen release (Bet v1) by air pollution (e.g., by NO or NO₂), increasing the intensity of allergic diseases (Pöschl, 2005). On the basis of the projected global climate change, particularly in cities, an increase in the pollen count, which is responsible for triggering allergies, is expected.

In regard to the influence of atmospheric particulate matter concentrations in Germany during calm and clear summer weather or heat waves, four main factor groups can be identified (Fig. 15):

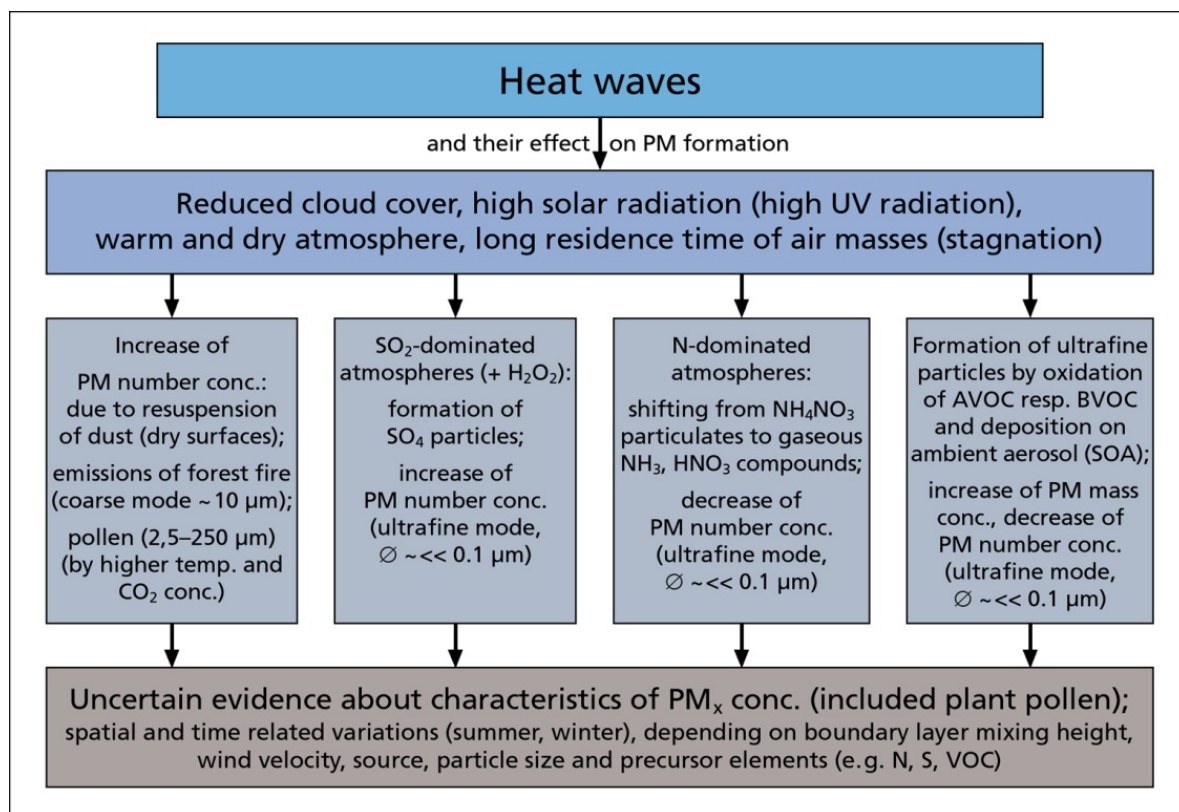


Figure 15. The influence of temperature on the formation of particulate matter (source: compiled according to Carvalho et al., 2010; Dawson et al., 2007; Jacob & Winner 2009; Pöschl, 2005; Wise & Comrie, 2005; Ziska et al., 2003)

1. Large (PM₁₀) and very large particles (< 250 µm) can be taken up from dry ground or surfaces in case of sufficiently high wind speed and shearing stress as primary or

resuspended dust, or be released from plants as pollen. Furthermore, forest fires can increase the particle concentration in the atmosphere.

2. Sulphate particles for instance can be formed in an SO₂-dominated atmosphere with the participation of H₂O₂, thereby increasing the particle number concentration in the ultrafine mode (PM_{0.1}).
3. An N-dominated atmosphere encourages, for instance, the conversion of NH₄NO₃ particles in the gaseous N compounds NH₃ and HNO₃, decreasing the particle number concentration in the ultrafine mode (PM_{0.1}).
4. AVOCs and BVOCs adhere to particles already present in the atmosphere due to their low vapour pressure. Therefore, no new formation occurs but, rather, an increase of mass.

In sum, both regional and seasonal aspects are found to exert diverse influences on the concentration of particulate matter.

4. Countermeasures on the local level

Countermeasures against global climate change being the sum of mitigation and adaptation measures should be taken particularly in cities. Although cities occupy only a relatively small proportion of the Earth's land mass, they are home to more than half the world's population. Consequently, cities are viewed as the strongest net sources of anthropogenic carbon dioxide (Büns & Kuttler, 2012; Grimmond et al., 2004; Velasco & Roth, 2010; Vogt et al., 2006).

Among other effects, the projected climate change (IPCC, 2007) will lead to an increase of temperatures during the entire course of the year in central Europe. The reduced requirement to remove snow and ice in the winter has to be emphasised as a positive effect, saving energy and costs (Brandt, 2007). Additionally, the heating costs of buildings and structures in the cold season should decrease, reducing CO₂ emissions.

These positive aspects of climate change are opposed by the known disadvantages in the summer, which are as follows:

- higher thermal stress for individuals;
- increased cooling requirements for buildings;
- increased spread of pathogens (mosquitoes, ticks) and allergy-triggering plants (e.g., Ambrosia);
- danger of flood and inundation caused by heavy rain.

Appropriate building-design and urban-planning measures are discussed in the following sections. These measures can counter the effects of overheating, which occur particularly in densely built-up urban districts. In this context it has to be considered that these temperature-reduction measures can prove effective only against autochthonous, dry heat. However, in allochthonous, humid and hot conditions, the measures are scarcely effective (Holst & Mayer, 2010).

4.1. Object-related means

Concerning central European climate, preventive object-related means to reduce CO₂ emissions are efforts to save energy in building air-conditioning. An example of such means would be to reduce the currently high specific heating-energy consumption of sometimes > 200 kWh/(m² a) in Germany. Better thermal insulation of buildings and resident consumption restrictions (Stadt Essen, 2009) could reduce this figure to ≤ 100 kWh/(m² a).

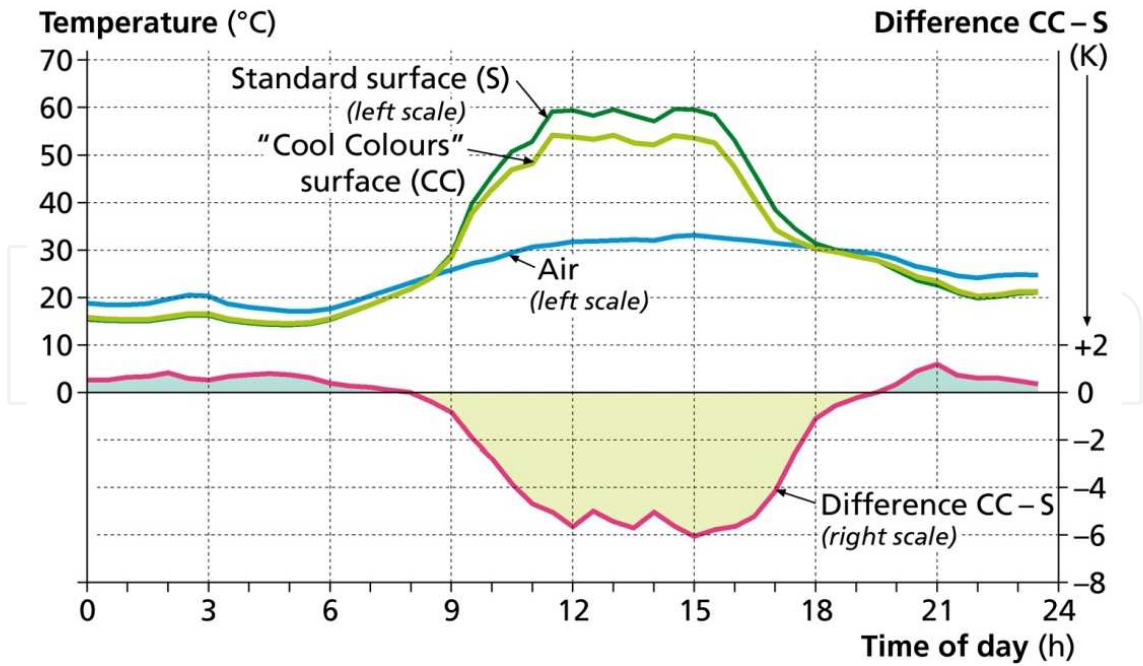
At 10 to 15 kWh/(m² a), significantly less energy is required by passive houses. Even better is the energy balance of plus-energy houses, which on a yearly basis generate more energy than they consume. Only when a household produces an energy surplus can an electric vehicle become feasible, because the vehicle's energy could be produced without the help of CO₂-emitting power stations (Hegger, 2009; in Germany, the CO₂-emission rate is approximately 0.6 kg CO₂/kWh).

Generally, the UHI effect means that the energy costs to keep inner-city buildings cool in the summer is higher than in the surrounding countryside. Consequently, office buildings in the City of London require 16 % more energy for cooling than comparable buildings in the surrounding countryside (Kolokotroni et al., 2006).

It is well known that brightly-coloured surfaces reflect more short-wave radiation than dark surfaces and therefore release significantly less long-wave radiation ($L\uparrow$) into the vicinity and via heat conduction (λ_s) into the ground or the building.

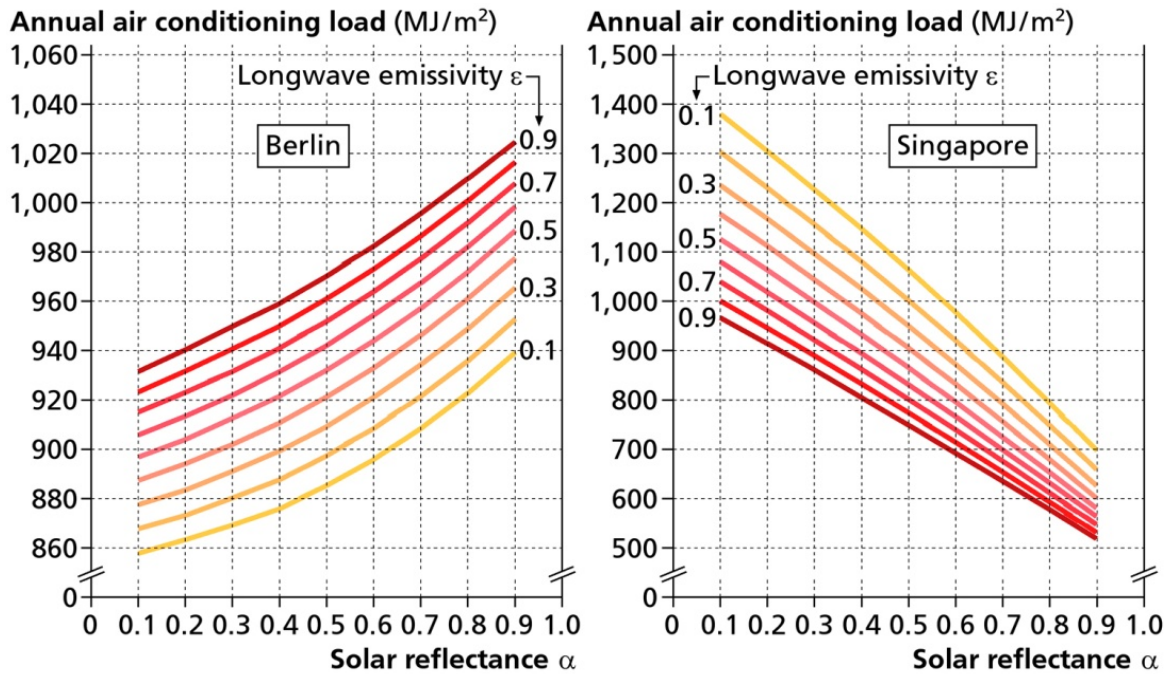
However, absorption cannot only be reduced by increasing the amount of reflection in the short-wave range. Additionally, if surfaces are coated or coloured to reflect infrared radiation (Cool Colours) the amount of reflection in the long-wave range can be increased. Comparative measurements (Fig. 16) show that during highest solar radiation a reduced surface temperature of up to 6 K is possible for a surface coated with Cool Colours in comparison with a standard surface due to a stronger reflection in the near-infrared range ($\lambda > 750$ nm). Because a surface coating of this type creates lower temperatures than a standard surface during intense solar radiation, less energy is conducted into the material and a reduction in long-wave radiation flux density ($L\uparrow$) is realised.

In the summer, highly reflective surfaces can lead to a noticeable reduction of temperatures and save cooling energy for buildings. However, in cold climates and during the heating period, building walls that are highly reflective are counterproductive in regard to the thermal balance because highly reflective walls do not help to achieve a solar radiation energy gain for the building when outside temperatures are low. Temperature-dependent, seasonally changing, thermochromic house colours (in summer: bright; in winter: dark) for a technical application do not yet exist. Thus, a compromise must be found that takes into account a house's yearly energy consumption for cooling and heating. Research conducted with model houses for different climate zones resulted in a highly differentiated picture. A location in the middle latitudes (Berlin, Fig. 17, left) shows that for annual energy consumption with respect to the short-wave albedo (α) and the long-wave emissivity (ε) of the surfaces, the lowest possible albedo values and equally low emission coefficients lead to



¹⁾ Site: University of Duisburg-Essen climate station, Campus Essen

Figure 16. The diurnal air-temperature progression for a standard surface (S), a Cool Colours-surface (CC) and their difference (CC-S) on a day with clear and calm weather in Essen (26.06.2010)¹⁾ (source: P. Wagner, pers. comm.)



¹⁾ one-storey house, flat roof; 20 m width, 20 m length, 4 m height; each wall has glass windows (16 m²) with a U-value of 3.2 W/(m² K); wall thickness: 0.28 m (bricks and cement mortar), $R_{th} = 0.42$ (m² K)/W; roof: 0.1 m reinforced concrete, 30 mm XPS board as insulation and 20 mm cement mortar, $R_{th} = 1.12$ (m² K)/W; ach (air change per hour): 0.3

Figure 17. Yearly energy consumption for heating and cooling a one-storey model house¹⁾ as a function of the wall's short-wave reflection (α) and long-wave emissivity (ϵ) (source: Shi & Zhang, 2011, modified)

the lowest annual energy consumption. Here, a low emissivity value offers the highest saving potential. For comparison, the juxtaposed example taken from the tropics (Singapore, Fig. 17, right) illustrates that in this climatic zone a house's walls should have the highest possible values of both coefficients. Here, a high albedo has the strongest influence compared with a high emissivity, when targeting the saving of energy for heating and cooling.

If buildings are greened, numerous micro-climatic and air-hygienic advantages can be identified. Among these advantages are lowered building surface temperatures during high radiation with less diurnal fluctuations in comparison with a building without vegetation (Alexandri & Jones, 2008). Furthermore, evergreen vegetation can protect the building against heat loss in the winter.

In addition, the green surface leads, as a function of the LAD, to ad- and absorption of atmospheric trace substances, frequently improving the air quality in the building's vicinity (Köhler, 1993).

Fig. 18 shows the substantial differences between the surface temperatures of different types of roofing during clear and calm weather in summer. Black roofing felt reaches a temperature of more than 90 °C for a short time around solar noon. Considerably lower values are measured for bright and dry gravel as well as bright paint. However, the lowest values are produced by artificially moistened and, in particular, watered and planted roofs. Between a watered and planted roof and the black roofing felt, a temperature difference of up to 70 K can be measured at approximately noon. Consequently, planted and watered roofs are among the most efficient measures to reduce surface temperature if the strongest cooling effect is desired at maximum radiation. At night, the surface temperatures of all roofs reach a similarly low level.

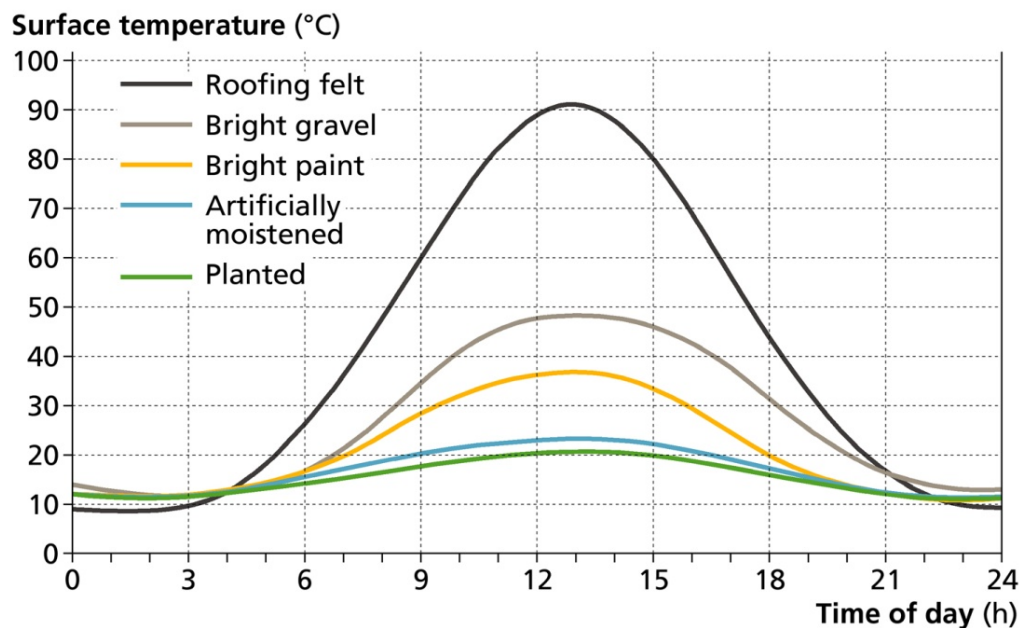


Figure 18. Surface temperatures of different roofs during clear and calm weather in summer (Berlin; source: Horbert, 2000, modified)

Planted roofs display similarly positive characteristics with respect to water budget when compared with roofs without vegetation (Table 3). The evapotranspiration of a green roof in regard to overall precipitation is substantially higher (72 %) than that of compared surfaces in a built-up area, even when in the case of a conventional roof, an additional partial evaporation of the run-off precipitation in swales and trenches (23 % and 10 %) is considered. Because the surface run-off of the green roof amounts to only 28 % in comparison with the conventional roof with 80 % and, furthermore, occurs after a delay, discharge peaks are reduced severely, leading to a balanced catchment yield factor. Because the frequency of strong rain is expected to increase in the future, a large-scale greening of roofs in developed areas would offer a possibility to mitigate the force of potential floods or prevent them.

	Water budget (% of precipitation)		
	Surface run-off		Groundwater
	Evapotranspiration	(including sewage water)	recharge
Natural predeveloped area			
Grassed area and cultivated land	55	9	36
Developed area			
Roof ¹	20	80	0
Green roof ¹	72	28	0
Traffic area	25	75	0
Water semi-permeable pavement ²	30	55	15
Swale infiltration ³	23	1	76
Trench infiltration ³	10	1	89
Undeveloped area (mixed vegetation)	65	7	28

¹ 70 % roof area with 45°-slope, 30 % with 2°-slope

² Average over pedestrian way and terrace

³ Roof run-off infiltration

¹⁾ Calculations were conducted with the analytical hydrological precipitation discharge model erwin 4.0 (2002). Green roof: sedum-grass-herb roof with an extensive substrate of 10 cm

Table 3. A water budget for representative land use with medium precipitation rates (799 mm/a)¹⁾ (source: Göbel et al., 2007)

Green roofs have undeniable climatic, air-hygienic and hydrological advantages for appropriately equipped buildings. For green roofs to exert a beneficial climatic influence on a larger scale, e.g., on the city-district level, as many houses as possible and in particular low houses should be greened.

4.2. Area-related means

Area-related means are interventions in solar-energy balances and the CO₂ budget of the UBL, here, however, relating to the scale of central city districts and urban residential quarters. A brief compendium of possible adaptation measures to climate change – of which

some will be discussed later – is presented in Table 4. These and more measures correspond to recommendations made by federal state governments in Germany for example. For a successful implementation of measures sufficient legislation is a prerequisite.

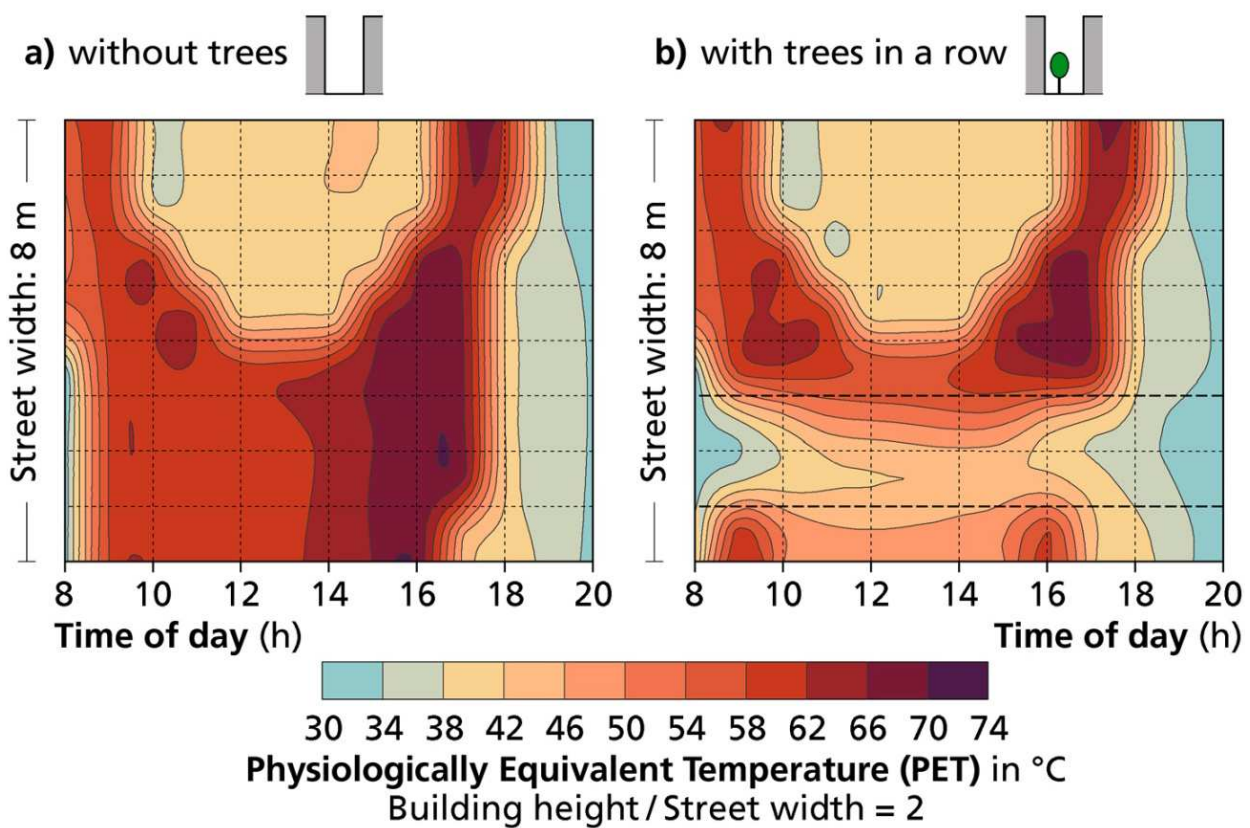
Residential quarters scale
<i>Built infrastructure</i>
Preserve and create open space; minimise impervious surfaces
Create open water bodies
Optimise building orientation to the sun
Provide shading of relevant spaces
Use building material with reduced heat conduction and heat storage properties; cool colours
<i>Green areas and vegetation</i>
Create, maintain, redesign parks
Provide greening of streets; use of suitable plants
Guarantee sufficient irrigation of urban vegetation
Increase the number of trees and shrubs for providing shade
Use plants that increase the permeability of the soil due to root and water penetration
City scale
Restrict building land to prevent urban sprawl
Preserve and/or create surfaces which produce fresh air
Preserve and create ventilation channels as links between rural and urban environment

Table 4. Selected area-related adaptation measures to climate change on the residential quarters' and city scale.

An important means to reduce thermal stress in cities and thereby adapt to the climate change is the shading, evaporative cooling and ventilation of appropriate spaces. The reduction of radiation and air temperature of squares and streets depends on a variety of factors (Erell et al., 2011; Holmer et al., 2007). These factors include the geometric settings produced by the building structures, the influences of which can be determined by the ratio building height to street width (H/W), the sky view factor (SVF) (Blankenstein & Kuttler, 2004; Synnefa et al., 2006), the ventilation degree, the shading possibilities, the ground colour (Synnefa et al., 2006) and the ground type (sealed/natural). The amount of shade produced by large-canopy roadside trees depends on the shape, size and density (LAI, LAD) of their crowns, among other factors (Erell et al., 2011; McPherson & Simpson, 1995). In addition, the location of the tree plays a crucial role for the area to be shaded (Donovan & Butry, 2009). Furthermore, a canopy cover in the middle of the road should be avoided if trees are planted on both sides because the tunnel effect created could lead to street-level exhaust-gas accumulation. Approximately 80 % of the cooling effect of trees results from the shade, and, where soil moisture is optimal, approximately 20 % results from the latent heat flux (Q_E) of evapotranspiration (Shashua-Bar & Hoffman, 2000). In addition to improving thermal comfort, trees contribute to a pleasant light climate by reducing UV radiation and long-wave radiation fluxes under the canopy (Holst & Mayer, 2010).

Fig. 19 displays the cooling effect of roadside trees during hot weather. The thermal comfort perceived by a person located in the shade is increased significantly as PET values are reduced up to 22 K. This effect can be attributed more to lower radiation temperatures than to transpiration. Outside the shade, only a minor effect on thermal comfort can be observed. The direct solar radiation (K_d) is considerably reduced by trees during the bright daylight hours (in this case, up to 850 W/m^2 ; Fig. 20, a) as is the long-wave radiation from the ground ($L\uparrow$) (by up to 200 W/m^2 ; Fig. 20, b), contributing essentially to improving thermal comfort.

A sunscreen can also be produced artificially, e.g., with covered footpaths or galleries (Ali-Toudert & Mayer, 2007), double-skin façades (Baldinelli, 2009), membrane structures covering semi-closed spaces (He & Hoyano, 2010) and canvas blinds or parasols. The reduction of radiation temperature can be substantial, improving the thermal comfort of the occupants and, by reducing the daily temperature range, countering the fatigue of material located in the shade. Additionally, light-induced ozone formation decreases.

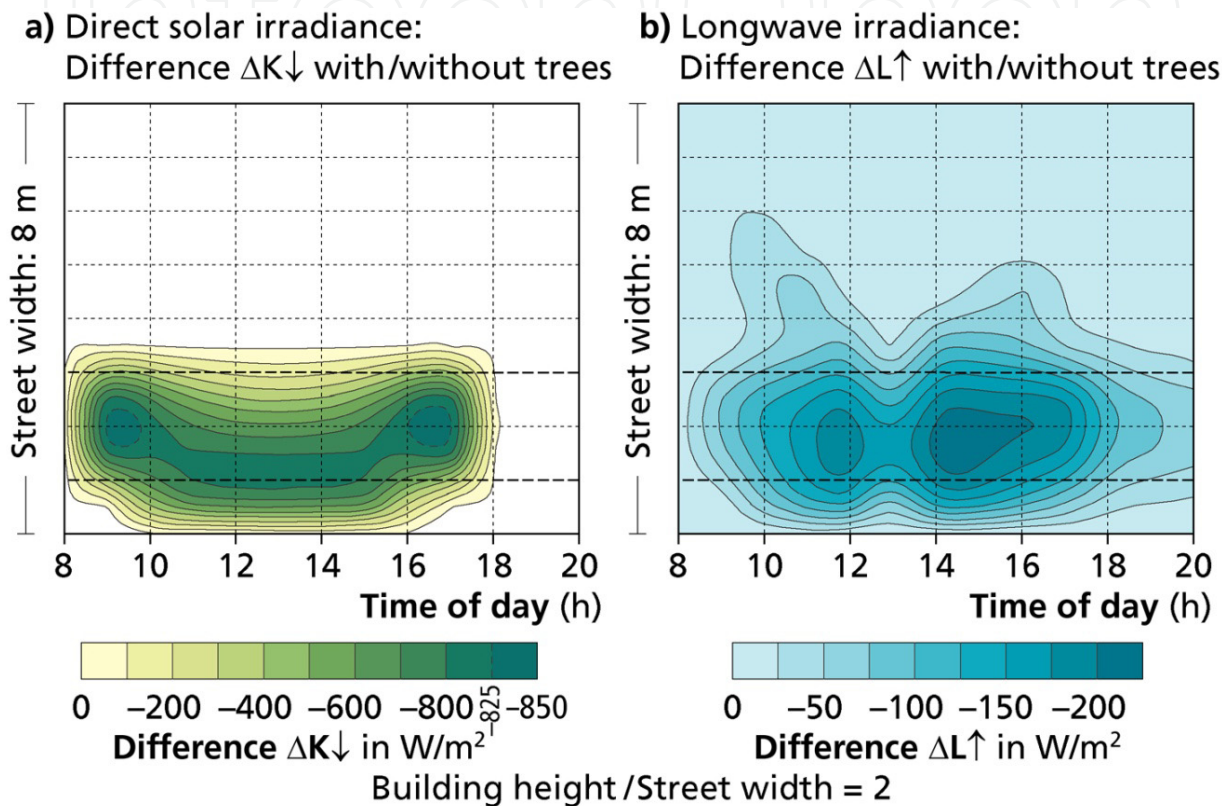


¹⁾ (E-W oriented; H/W = 2; tree row on the north side of the street; tree height: 10 – 16 m, dense treetops; PET > 42 = very hot)

Figure 19. The effect of roadside trees on thermal comfort (PET) in a street canyon¹⁾ in central-Saharan Ghardeia, Algeria (source: Ali-Toudert & Mayer, 2007, modified)

Green areas with grass only, often found as city greens, contribute little to the improvement of urban climatic conditions during the day because these areas provide little or no shade and exert their climatic influence largely through the latent heat flux (Q_E) caused by evapotranspiration, which depends on sufficient soil moisture.

As Fig. 21 illustrates, the surface temperature of grass-covered areas increases significantly with the passing of precipitation-free hours, which means that the climatic effects of grass-covered areas are closely linked to the soil's water supply. If the area dries out for a few days (here, a maximum 11 d), the desired effect of temperature reduction increasingly disappears. Intra-urban (grass-covered) green areas should therefore be optimally supplied with water to maintain and ensure their beneficial thermal effects on the local climate, particularly in hot weather.

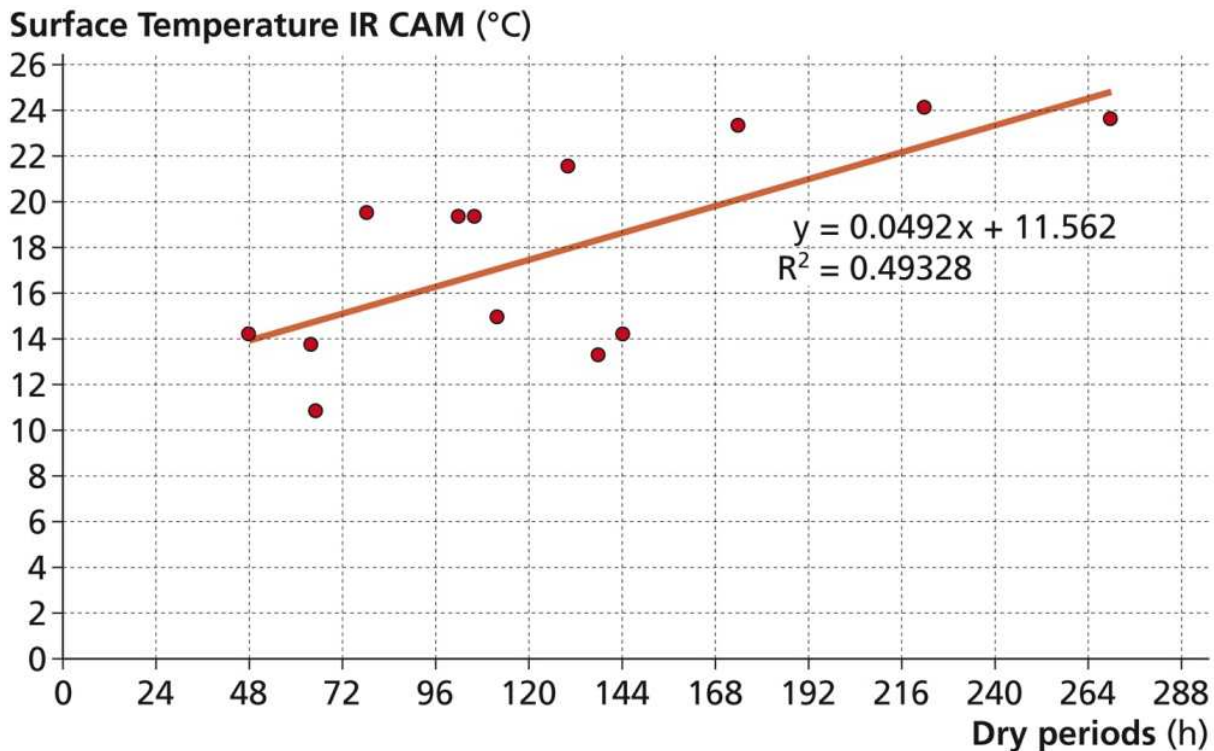


¹⁾ (E-W oriented; H/W = 2; tree row on the north side of the street; tree height: 10 – 16 m, dense treetops)

Figure 20. The difference between (a) direct solar radiation (ΔK_{\downarrow}) and (b) long-wave radiation of the street surface (ΔL_{\uparrow}) in a street canyon¹⁾ with/without a tree row in central-Saharan Ghardeia, Algeria (source: Ali-Toudert & Mayer, 2007, modified)

Because their deposition velocities (v_d) reach only low values in comparison with other vegetation (Horbert, 2000; Litschke & Kuttler, 2008), grass-covered areas adsorb and absorb relatively small amounts of air pollutants. In contrast, the combination of greater volume and the reduced wind velocity caused by trees in wooded green areas results in an effective filtration of the air beneath the canopy. For example, coniferous trees can filter a multiple of trace substances compared with an open area by dry and wet deposition (Wrzesinsky, 2004). The type and density of vegetation, particularly LAI, play a crucial role in the absorption of particles and gases (compilation in Jonas et al., 1985; Litschke & Kuttler, 2008).

For example, 200 m from an intensively used road, mitigation values between 40 % and 50 % could be determined as the annual mean values for the atmospheric trace substances



¹⁾ 14., 16., 22., 23., 26., 28., 30.09.; 15., 17., 21., 24., 27., 31.10.2011

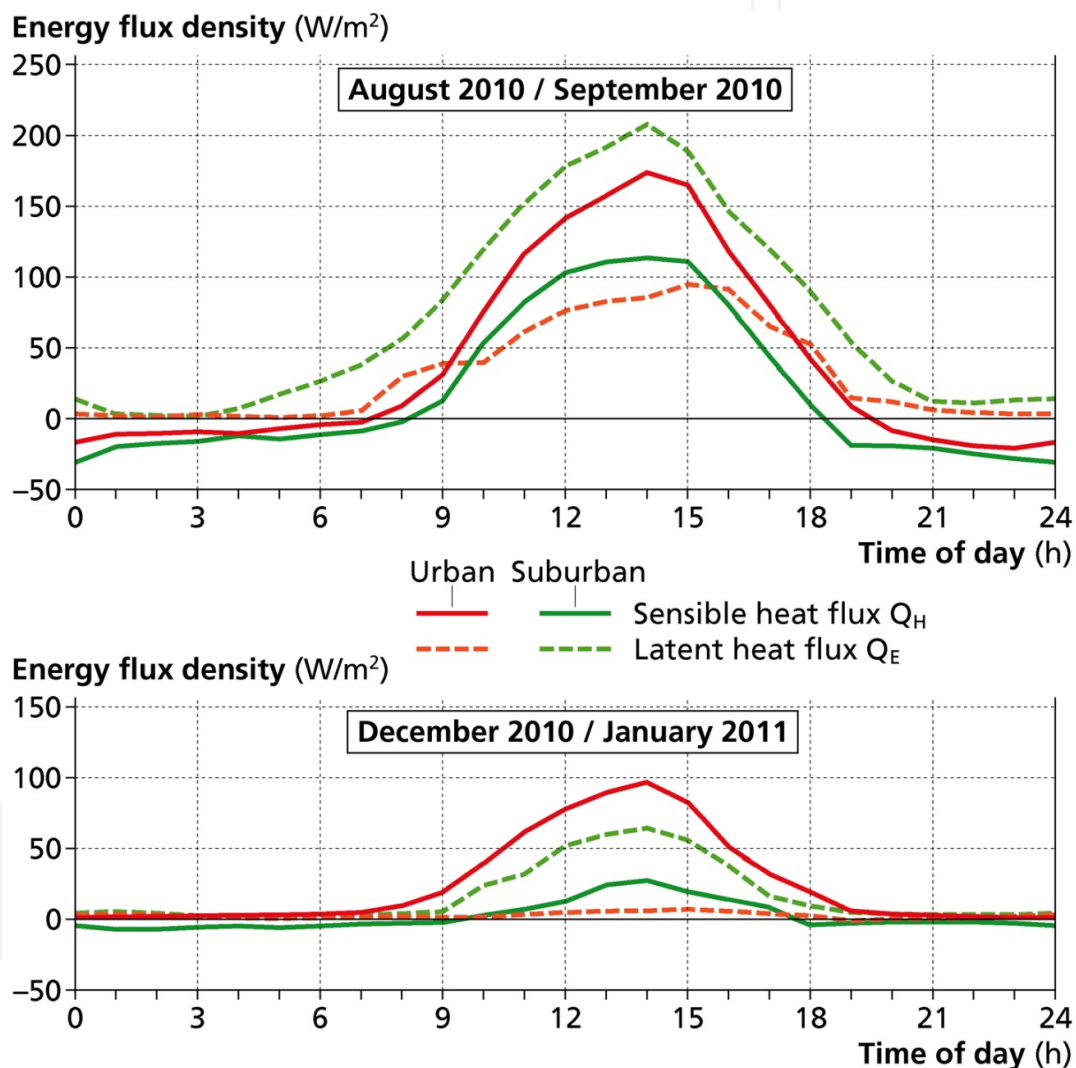
Figure 21. The surface temperature of a grass-covered area at the University of Duisburg-Essen climate station as a function of the number of precipitation-free hours¹⁾

NO and NO₂ in a green area (grass, trees and shrubs) and a 20 % reduction of the immission concentration of CO compared with concentrations measured at the roadside. However, the ozone concentrations in the green area were up to 20 % higher than at the street location (Ropertz, 2008).

The positive thermal effect of green spaces with trees and shrubs in comparison with sealed surfaces becomes clear when the turbulent heat flux densities (Q_H , Q_E) of an urban ($\lambda_P = 0.82$) and a suburban location ($\lambda_P = 0.31$) (Fig. 22) are juxtaposed. While the turbulent sensible heat flux (Q_H) dominates at the urban location in summer and in winter, the turbulent latent heat flux (Q_E) constantly reaches higher values than Q_H at the planted and irrigated suburban location (wooded grassland). At the urban location, the mean Bowen ratio ($\beta = Q_H/Q_E$) amounts to $\beta_u = 1.8$ in the summer and $\beta_u = 21.4$ in the winter. The conclusion can be drawn that because of the limited availability or absence of water, far more energy is used for the heating of the air than for the evaporation. In contrast, the β -values reach the expected significantly lower values of $\beta_{sub} = 0.5$ at the suburban location in the summer and in the winter, as opposed to the urban location. Applying the proportion of Q_E to the radiation balance Q^* , it becomes clear that at the urban location on days with clear and calm weather in the summer only 23 % and in winter only 4 % of the energy can be dissipated by evaporation. At a suburban location, these proportions are higher: 54 % in summer and 41 % in winter. Additionally they fluctuate much less than in the city because of the optimal availability of water in the diurnal course. At a suburban location, the value of Q_E occasionally exceeds the value of the radiation balance Q^* , particularly in the afternoon

hours (not shown here). Such episodes are called the oasis effect because a high evaporation potential cannot be covered by Q^* and therefore draws energy from the surroundings to compensate the radiation balance, cooling the vicinity.

The comparison shown in Fig. 22 illustrates that green areas, which have a high evapotranspiration potential if supplied well with ground water, can contribute significantly to improved thermal comfort. From the urban-planning perspective, increased attention should be paid to this contribution because heat waves will occur more frequently in the future. However, a sufficient supply of irrigation water must be ensured (see above, Cleugh et al., 2005).



¹⁾ 08/2010 – 09/2010: 10 days with calm and clear weather; 12/2010 – 01/2011: 8 days with calm and clear weather

Figure 22. Average diurnal courses of turbulent heat flux densities (Q_H , Q_E) at an urban and suburban site¹⁾ in Oberhausen, Germany (source: Goldbach & Kuttler, 2012)

A sufficient supply of water can be ensured by skillfully designing areas for the collection and storage of rainwater, thereby preventing a sewage-system overload in case of heavy rainfall.

Due to the mostly lower temperatures of urban green areas as compared with the warmer built-up areas in their vicinity, the green areas are called “urban cold islands” (Bongardt, 2006).

The lower temperatures of the green areas can generate a local circulation between the green areas and the built-up neighbourhood. Such local air movements, called park winds, reach only low speeds and occur more intermittently than continuously. The extent to which the cool air flows into the built-up surroundings depends on the design and enclosure of the green area and the type of the surrounding buildings and structures. For instance, if the green area is located in a ground depression or is surrounded by a high wall, the air-exchange rate will be reduced and the spread of cool air into the built-up area restricted. However, wall apertures in combination with streets at right angles can assume the functions of ventilation channels and lead cold air into the street canyons.

The questions of how large a green area must be to cause a temperature reduction and up to what distance from the green area into the built-up surroundings a temperature-reducing effect can be proven are highly relevant to climatological urban planning. Generally, a connection between the size of a green area and a higher thermal spread seems likely (Hamada & Ohta, 2010). To what degree this phenomenon occurs can be seen in Table 5.

Size in ha (rounded)	Location (UHI in K)	Park	Structure	PCI _{max} in K	Reach in m	Source
3	Kumamoto (Kyushu) (3 day, 2 night)	Kengun Shinto Shrine	Trees	2.5 (3 p.m.)	50	Saito et al., 1990
5	Vancouver (6 at dusk)	Trafalgar Park	Grass, tree fringe partly irrigated	5.0 (night) mobile measurements	200 - 300	Spronken-Smith & Oke, 1998
10	Dortmund	Westpark	Grass and trees	4.0 (night)	150	Bongardt, 2006
18	Berlin	Stadtpark Steglitz	-	1.0 (evening)	80 - 140	von Stülpnagel, 1987
30	Mainz	Stadtpark	-	2.0 (morning)	< 300	Naumann, 1981
44	Stuttgart	Schlossgarten	-	1.3 (yearly mean) 3.8 (daily mean)	200	Knapp, 1998
80	Copenhagen	Falledparken	Grass and trees	2.1 (10 p.m.)	100	Eliasson & Upmann, 2000
125	Berlin	Kleingärten Priesterweg	Garden	5.4 (evening)	250	von Stülpnagel, 1987
156	Gothenburg	Slottsskogen	-	3.3 (6 p.m.) measuring station	250	Eliasson & Upmann, 2000
212	Berlin	Tiergarten	Forest / grass	4.3 (evening)	200 - 1,300	von Stülpnagel, 1987
525	Mexico City	Chapultepec	Mixture (trees, grass); not irrigated	4.0 (dry season) 1.0 (wet season)	2,000 (one park depth)	Jauregui, 1990

Table 5. A compendium of size, surroundings, maximal cooling effect (PCI_{max}) and thermal reach of urban green areas (source: according to a compilation in Bongardt, 2006; here, according to Kuttler, 2010b, modified)

Because frequently higher summer temperatures and a lower amount of precipitation are expected due to the climate change, plants with high drought tolerance should be used in urban green areas. Additionally, which plants release significant quantities of BVOCs during high temperatures should be considered. Mainly those plants should be used that

are low-emitters of isoprene (Benjamin & Winer, 1998; Taha, 1996), which are plants with isoprene emissions during thermal stress of not more than 2 µg per g dry matter per hour. Table 6 displays selected trees characterised by a low ozone-forming potential and optimal drought tolerance in case of limited water supply.

Scientific name	Common name	Low ozone-forming potential (OFP)	High drought tolerance (DT)
<i>Acer campestre</i>	Field Maple	++	++
<i>Acer rubrum</i>	Red Maple	++	++
<i>Carya ovata</i>	Shagbark Hickory	++	+
<i>Carya tomentosa</i>	Mockernut hickory	++	++
<i>Fraxinus pennsylvanica</i>	Green Ash, Red Ash	++	+
<i>Ginkgo biloba</i>	Ginkgo, Maidenhair Tree	++	++
<i>Malus tschonoskii</i>	Tschonoski Crabapple, Pillar Apple	++	+
<i>Pinus ponderosa</i>	Ponderosa Pine, Bull Pine, Blackjack Pine	+	++
<i>Pinus sylvestris</i>	Scots Pine	+	++
<i>Prunus avium</i>	Wild Cherry, Sweet Cherry, Bird Cherry, Gean	++	++
<i>Pyrus communis</i>	European Pear	++	+
<i>Pyrus pyraeaster</i>	European Wild Pear	++	+
<i>Quercus rubra</i>	Northern Red Oak, Champion Oak	+	+
<i>Sophora japonica</i>	Pagoda Tree	+	++
<i>Ulmus parvifolia</i>	Chinese Elm, Lacebark Elm	++	+
<i>x Cupressocyparis leylandii</i>	Leyland Cypress	++	+
<i>Zelkova serrata</i>	Japanese Zelkova, Keyaki	++	+

Low OFP: Isoprene emission 2µg/(g·h) DT; ++ = very good, + = good

Table 6. The ozone-forming potential (OFP) and drought resistance of selected trees and their suitability to higher temperatures (source: combined according to Benjamin & Winer, 1998; Roloff et al., 2008, modified; here, according to Kuttler, 2011b)

Cities require a great amount of parking space. For instance, parking space amounts to approximately 10 % of the city area in the USA and almost 7 % in Japan (Onishi et al., 2010). Because most of this space is covered with tarmac or paved and absorbs a great amount of heat due to the dark colour, the shading or greening of these surfaces would have a substantial positive effect on the energy balance. In comparison with an area of tarmac, a grassy parking area displays a maximal temperature difference of the surface of up to 15 K during calm and clear summer weather with maximum solar radiation values. During the daytime, the sensible heat flux can be reduced by 100 to 150 W/m² and in the night by approximately 50 W/m² based on investigations in Japanese cities (Takebayashi & Moriyama, 2009). This demonstrates that greened parking areas can limit or reduce the sprawl and intensity of the UHI effect even in the night, at least locally. However, this reduction is only possible for intact and irrigated stretches of grassy areas. If the turf is damaged, the cooling effects are severely limited (Kanemoto et al., 2009).

The following overview summarises the climatic and air-hygienic effects as well as the climate-related design recommendations for intra-urban green spaces (according to different authors):

- reduction of surface and air temperatures by means of shading and evapotranspiration ($q_{v,W 20^\circ\text{C}} \sim 2.4 \text{ MJ/kg water}$; negative correlation of surface temperature with the normalised difference vegetation index (NDVI))
- significantly higher avoidance of CO_2 production in the city with the help of city trees compared with similar forest trees (in its CO_2 -reducing effect, one urban shade tree equals several forest trees)
- decrease of net CO_2
- creation of a pleasant light climate (shift of reflected and transmitted radiation to the long-wave section of the radiation spectrum, reduction of UV radiation)
- reduction of the wind speed and therefore the possibility of trace-substance deposition on plant surfaces, albeit a danger of atmospheric pollutant accumulation (tunnel formation in street canyons)
- reduction of discharge peaks because of interception and time-delayed percolation of precipitation into the ground
- decrease of ozone-formation potential by reduction of ambient temperatures
- large areas should be planted following the “savannah principle”: grass and interspersed solitary canopy trees with shading effects
- green aisles should be designed with minimum roughness and connected linearly if possible
- intra-urban areas or areas close to the city should be planted with “energy plants” (e.g. poplars)
- green spaces in suburban areas should be preserved for the regeneration of cold and fresh air
- exploitation of the “shrinking cities problem” to transform sealed surfaces to green areas and water-retentive areas

Finally, it should be noted that shading, greening or surface brightening during periods of high summery radiation can have direct or indirect effects on buildings or city districts, leading not only to lower temperatures but also to a decrease in energy consumption by the reduced use of air-conditioning systems.

5. Energetic use of the urban subsurface

The excess heat of sealed surfaces in urban areas can be used to save energy expended on controlling the climate of buildings and thereby reduce urban CO_2 emissions. Because this overheating also occurs below the surface (subterranean UHI; see chapter 1), the intensity and frequency of the overheating must be established. As the exemplary data collected in Oberhausen, Germany, demonstrate (Fig. 23), the temperatures measured at up to 2 m depth (daily mean values) are predominantly higher (with the exception of April/May) than the air temperatures measured at the same location. If the average temperature difference (ΔT_{a-s}) between the air (t_a) and 2 m below ground (t_s) is approximately 2 K and the relevant urban area has a size of 2 km^2 , this temperature difference would represent approximately $2.2 \cdot 10^6 \text{ kWh/a}$. Assuming a ground thermal capacity density of $\zeta = 2 \cdot 10^6 \text{ J/(m}^3 \text{ K)}$ and a

complete use of the temperature difference for a layer thickness of 1 m. If used via a heat pump with an efficiency of $\eta = 0.5$, this energy would amount to the annual energy consumption of approximately 275 German households (4 persons; 4,000 kWh/a) and, based on an emission of 0.6 kg CO₂/kWh (German power plant mix), lead to an avoided emission of approximately 660 t CO₂. Because the temperature difference between the air and the ground is not constantly 2 K but fluctuates, this energy should be used to heat water for domestic use with the possibility to be stored to bridge periods without heat-pump energy.

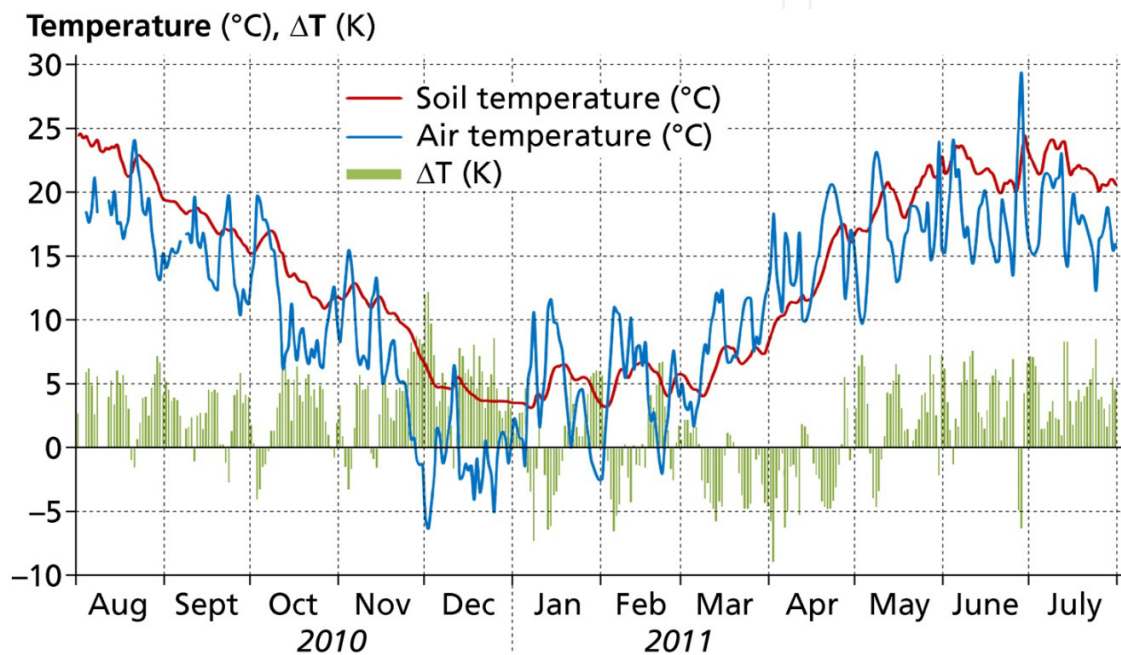


Figure 23. Daily mean values of air temperature (2 m above ground) and subterranean (2 m below ground) temperatures in Oberhausen, Germany, and their difference for the period 08/2010 – 07/2011 (source: H. Püllen, pers. comm.)

The energy yield of the subterranean UHI can be increased if the energy content of the groundwater could be used. As the exemplary temperature measurements in wells (Cologne, Germany) show (Zhu et al., 2010), water temperatures of 16 °C can be found below the inner city at a depth of 15 m, whereas under less densely built-up city districts, only 11 °C are reached (Zhu et al., 2010). Assuming a difference of approximately 5 K, a thermal capacity of at least $4.8 \cdot 10^{10}$ kJ can be calculated for a layer thickness of approximately 10 m and an area of 1 km². If the energy requirements for buildings are approximately $1.9 \cdot 10^{10}$ kJ/(km² a) in Cologne, the subterranean UHI can provide at least 2.5 times the energy required for heating and cooling buildings in Cologne. For this estimate, an energy supply for a building of approximately 50 kWh/(m² a) was assumed (Zhu et al., 2010). In addition to the energy savings, an emission reduction of approximately 3,000 t CO₂/(km² a) could be achieved in this case.

6. Outlook

Urban climate-change mitigation measures, such as surface unsealing, greening, preservation or designation of ventilation aisles, networking corridors or subterranean energy use, require space. However, space is often not available. In German cities, the current building-renewal rate is estimated at no more than 2 %/a. In the short term, the implementation of mitigation measures is rather improbable.

The former industrial cities are an exception. Here, structural change allows the reallocation of antiquated and vast industrial estates to new uses. In addition, the population decrease that can be observed in some cities enables the greening of open residential areas (Oswalt & Rieniets, 2006) and thereby the prevention of overheating.

Urban planning that takes climate change into account should favour compact but open building structures equipped with sufficient open spaces and green areas and offering possibilities for shading. Readily available public transport would obsolete the use of individual vehicle transport in the inner cities ("city of short distances"), thus reducing the emission of exhaust gases, particulate matter and CO₂. Building density and shading possibilities should be designed to provide sufficient protection against solar radiation in the summer while guaranteeing a maximum of radiation absorption in the winter. Suburban growth ("urban sprawl"), which has been monitored in numerous locations for some time now, should be superseded by suburban cold-air formation areas to provide the optimal ventilation of urban centres with fresh air from the surrounding countryside.

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